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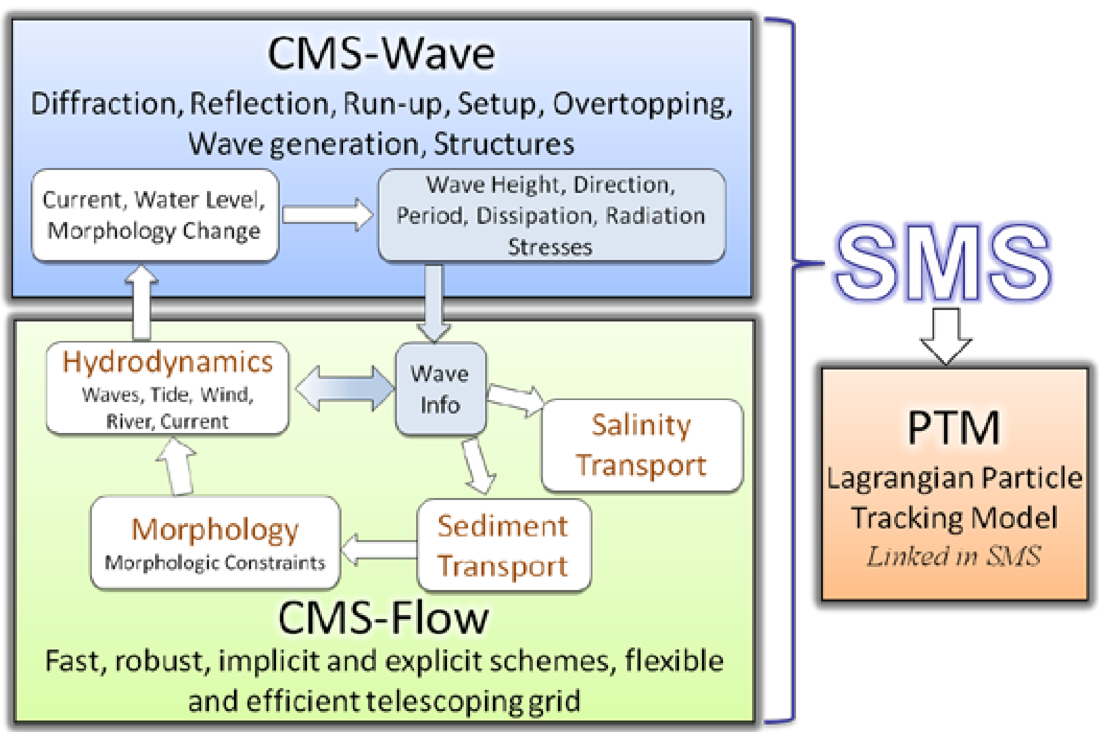
Verification and Validation of the Coastal Modeling System

Report 1: Summary Report

Zeki Demirbilek and Julie Rosati

December 2011



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Report 1: Summary Report

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Report 1 of a series

Abstract: This report summarizes the framework and provides key findings of the Verification and Validation (V&V) study for the Coastal Modeling System (CMS), a product of the Coastal Inlets Research Program (CIRP). There are three components of the study: Verification, Calibration, and Validation, and these are termed for simplicity as "V&V" herein and in the companion reports. This is the first report, Report 1, in a series of four reports, and it provides a synopsis of the major findings from the other three reports. Verification and Validation was performed for three main components of the CMS: CMS-Wave (Report 2), CMS-Flow: Hydrodynamics (Report 3), and CMS-Flow: Sediment Transport and Morphology Change (Report 4). This Summary is intended for engineers and scientists considering whether the CMS would be appropriate for their projects (after which they may study the other V&V reports) and for managers and decision-makers so that they will have a succinct resource detailing the performance of each CMS component as well as the integrated modeling system.

The overall V&V study was separated into three functional areas to assess the predictive skills of the CMS critically; specifically, for modeling waves, circulation, and sediment transport and morphodynamics for a wide variety of coastal inlet, navigation channel, bay, estuary, and adjacent beach problems. To achieve this goal, each evaluation began by verification of the model of focus by comparing its predictions to analytical or empirical solutions for purposes of testing the basic physics and computational algorithms implemented in a given model. These fundamental evaluations were followed by a set of applications with data available either from laboratory or field investigations, which were used to validate the models. The validation cases represent real world problems, typical applications for which CMS is applied within the coastal navigation mission area. For the Hydrodynamics Flow, and Sediment Transport and Morphology Change applications, the CMS suite of models were calibrated prior to validation using data from a number of past and present District project applications with measured data.

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Preface

This study was performed by the Coastal Inlets Research Program (CIRP), which is funded by the Operation and Maintenance (O&M) Navigation business line of the Headquarters, U.S. Army Corps of Engineers (HQUSACE). The CIRP is administered for Headquarters by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS, under the Navigation Program of HQUSACE. James E. Walker is HQUSACE Navigation Business Line Manager overseeing the CIRP. Jeff Lillycrop, CHL, is the ERDC Technical Director for Navigation. Dr. Julie Rosati, CHL, is the CIRP Program Manager.

The CIRP's mission is to conduct applied research to improve the USACE's capabilities to manage federally maintained coastal navigation inlets, which are present on all coasts of the United States including the Atlantic Ocean, Gulf of Mexico, Pacific Ocean, Great Lakes, and U.S. territories. The objectives of the CIRP are to advance knowledge and provide quantitative predictive tools to (a) support the management of federal coastal inlet navigation projects to facilitate more effective design, maintenance, and operation of channels and jetties to reduce the cost of dredging, and (b) preserve the adjacent beaches and estuary in a systems approach that treats the inlet, beaches, and estuary as sediment-sharing components. To achieve these objectives, the CIRP is organized in research work units conducting a wide range of applied Research and Development (R&D) related to waves, hydrodynamics, and sediment transport and morphology change modeling specifically for navigation channels, inlets, ports and harbors, adjacent beaches, navigation in estuaries, navigation and inlet structures, laboratory and field investigations, and technology transfer.

For its mission-specific requirements, the CIRP has developed CMS-Wave, a phase-averaged spectral wave model for inlets, navigation, and nearshore project applications. For the hydrodynamics, CMS-Flow, a shallow-water equations based model, has been developed, which is coupled to the wave model. The wave and hydrodynamics models are tightly integrated with the sediment transport and morphological change modules which perform short- and long-term predictions of the transport and bed change estimates in District navigation projects. The sediment transport and morphological change calculations are part of the CMS-

Flow, and these are not separate or stand-alone libraries. This tightly integrated system is called the "Coastal Modeling System" (CMS), and consists of modeling tools for nearshore waves, flow, and sediment transport and morphology change affecting the planning, design, maintenance, and reliability of federal navigation projects.

This report is part of a volume and must be viewed as a precursor to the other three companion reports which address technical issues in depth. Because it serves only as a primer to other reports, the technical rigor described in its companion reports is not duplicated in this report. After providing a summary of the CMS, it focuses heavily on the importance and justification of validation and verification by establishing an outline of the Verification and Validation (V&V) study undertaken to assess the skills and versatility of the CMS in Corps projects. This V&V study is comprehensive in scope, and focused on the coastal processes most affecting the Corps O&M navigation budget. The objectives of the entire CMS V&V study were to evaluate both the CMS wave and flow models independently, then together as an integrated modeling system for different wave, hydrodynamic, and morphology change problems in coastal applications, and identify potential improvement areas for computational capabilities and new features needed to address District project needs. This Report 1 in the series provides an outline of the CMS V&V study, including a summary of the study results, major findings, and recommendations.

The following are all associated with ERDC-CHL, Vicksburg, MS. This report was prepared by Dr. Zeki Demirbilek, Harbors, Entrances and Structures Branch; and Dr. Julie D. Rosati, Coastal Processes Branch. Appendix B is available from the CIRP website and was provided by Mitchell E. Brown, Coastal Engineering Branch. This work was performed under the general administrative supervision of Dr. Jackie S. Pettway, Chief of Harbors, Entrances and Structures Branch; Dr. Ty V. Wamsley, Chief of Coastal Processes Branch; Dr. Rose M. Kress, Chief of Navigation Division; and Bruce Ebersole, Chief of Coastal Flood Damage Reduction Division. Drs. Ty V. Wamsley, Richard Styles, and Lyndell Z. Hales reviewed this report. Donnie F. Chandler, ERDC Editor, ITL, reviewed and edited the report. Jose Sanchez and Dr. William D. Martin were Deputy Director and Director of CHL, respectively, during the study and preparation of this report.

COL Kevin J. Wilson was ERDC Commander. Dr. Jeffery P. Holland was ERDC Director.

Unit Conversion Factors

Multiply	By	To Obtain
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
Feet	0.3048	meters
Knots	0.5144444	meters per second
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters
miles per hour	0.44704	meters per second
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per square foot	47.88026	pascals
square feet	0.09290304	square meters
square miles	2.589998 E+06	square meters
tons (force)	8,896.443	newtons
tons (force) per square foot	95.76052	kilopascals
Yards	0.9144	meters

1 Introduction

1.1 Background

The United States, through the U.S. Army Corps of Engineers, has national interest in the stability and evolution of coastal inlet navigation channels, navigation structures, and adjacent beaches. Nearly $2 billion of the Corps Operation and Maintenance (O&M) budget is expended annually to operate and maintain federal coastal navigation projects including channels, inlets, associated jetties, and breakwaters; and adjacent beaches, estuaries, and intercoastal waterways. The physical processes of coastal inlets extend beyond coastal navigation and shore protection, also affecting the coastal environmental missions of the Corps and the Nation's economic strength. As such, coastal inlets are:

- Vital commercial and military navigation links.
- Closely connected to beach stability and estuary health, locally and regionally.
- Central for exchange of water, sediment, and nutrients between estuaries and seas.
- Recreational opportunities for the nation and assets for the economic strength of coastal communities.

Multiple interacting meteorological and oceanographic (metocean) forces affect Corps coastal navigation and inlet projects. The range, magnitude, and interaction of these forcings cause numerous spatial scales of geomorphic changes at coastal inlets at temporal scales ranging from hours and days associated with tides and storm events, to years and decades over which long-term changes occur. The physical processes at coastal inlets are dynamic and complex and, in spite of significant advances that have been made in the last 30 years, some processes are extremely challenging and still remain poorly understood. For example, few quantitative predictions and data are available to estimate infilling of navigation channels, long-term changes in the nearshore that affect channel and jetty stability, collective morphologic evolution, short- and long-term migration trends and cycles of inlets, and the interactions among inlets, adjacent beaches, bays, and estuaries. The Coastal Inlets Research Program (CIRP) was established to address these and related technical needs of USACE O&M navigation business line.

The Research and Development (R&D) objectives of the Coastal Inlets Research Program (CIRP) include advancing the state of knowledge and developing engineering technology to predict waves, current, sediment transport, and morphology change at and around inlet navigation systems. The CIRP modeling capabilities are vital to USACE in management, design, and rehabilitation of coastal inlet navigation channels and structures through increased reliability of actions and reduction in operation and maintenance costs. The CIRP technology is targeted for desktop computers and can be learned and utilized readily by USACE District engineers and scientists. The development of technology is pursued by study of concepts and theory for all relevant time scales, quantifying these concepts through models for numerical simulations, collection of field data to test and validate formulations, and experimentation in the controlled laboratory environment to extend knowledge. The CIRP products include the Coastal Modeling System (CMS), as well as related reports and peer-reviewed articles which provide the information gained from the CIRP to the USACE, the scientific community, and the public. CMS is the flagship modeling system the CIRP has developed and because it continually evolves, it is necessary to make sure its predictions are reliable. This is the primary purpose of the Verification and Validation (V&V) study conducted by the CIRP. A brief description of CMS and its features follows. Additional information on CMS is provided in Chapter 2 of this report.

The CMS is an integrated suite of numerical models for simulating flow, waves, and sediment transport and morphology change in coastal areas. The system is designed for practical applications in navigation channel performance, and sediment management for coastal inlets and adjacent beaches to better manage and prioritize expenditure of USACE O&M funds. The CMS is intended as a research and engineering tool for desk-top computers, and uses the Surface-water Modeling System (SMS) interface for grid generation and model setup, as well as plotting and post-processing.

There are two models in the CMS: the wave (CMS-Wave) and hydro-dynamic (CMS-Flow) models. The latter includes sediment transport and morphology change, and therefore, there are three main components of the CMS: waves, flows, and sediment transport. Report 2 of the V&V study discusses features of the CMS-Wave model, including details of its V&V evaluation in a large number of applications, and documents the model's performance skills. The hydrodynamics, and sediment transport and

morphology change aspects, of CMS are presented in V&V Reports 3 and 4, respectively, with details of the V&V studies conducted, including the types of applications considered and corresponding performance statistics. Reports 3 and 4 also describe model calibration conducted in a variety of laboratory and field studies as a precursor to model validation.

1.2 Purpose of study

The objectives of the entire CMS V&V study were to evaluate both the CMS wave and flow models independently, then together as an integrated modeling system for different wave, hydrodynamic, and morphology change problems in coastal applications, and identify potential improvement areas for computational capabilities and new features needed to address District project needs. This Report 1 in the series provides an outline of the CMS V&V study, including a summary of the study results, major findings, and recommendations. After mathematical and computing fundamentals are verified, individual components and the integrated models of the CMS are evaluated by comparing performance of wave, hydrodynamic and sediment models to data available from a variety of field and laboratory studies. Because the companion V&V Reports 2, 3, and 4 provide a detailed description of the setup of CMS, forcing conditions, computational parameters, model-data comparison, and user guidance for applying CMS in Corps navigation projects, these are not repeated here.

There are three components of the V&V study: Verification, Calibration, and Validation. Each of these is a technical term with a specific purpose; however, these words are often used interchangeably in the engineering realm. Verification is pre-requisite to a model's release and is performed during its development to test correct implementation of the model's basic physics and governing equations. Calibration follows verification of a model, and generally involves tuning model empirical and computational coefficients to reproduce a measured or understood response. Calibration is required particularly for simulations of the flow and sediment transport in which there are many poorly-understood processes and empirical relationships. Data are required for calibrating a model. Validation follows model calibration, and is conducted without changing the model coefficients or setup parameters to reproduce additional measurements or known behavior. Validation assesses the model's overall skills to reproduce the processes in the real world (prototype) settings and determines whether or not a model is ready for practical applications.

The above distinctions between Verification, Calibration, and Validation are crucial to a clear and accurate understanding, interpretation, and application of the work described in this report and its three companion reports. The results provided in this V&V study are based on the available engineering data, and indicate the best way of applying the CMS models to various applications each with some unique characteristics. Chapter 2 provides specifics of the V&V study conducted to evaluate the CMS.

1.3 Report organization

This report is organized as follows. Chapter 1 gives an introduction to the V&V study and Report 1, which serves as a Summary of the V&V reports. Chapter 2 presents an overview of the CMS and discusses the strategy and plan for the V&V studies, including a detailed definition of terminology. Chapter 3 summarizes the V&V findings for the wave, hydrodynamic, and morphologic change components of the CMS. Chapter 4 is a concluding chapter that includes a summary and recommendations. The References chapter is extensive, and for completeness, all references used in Reports 2, 3, and 4 have been provided for the reader's information.

Appendix A presents the goodness-of-fit statistics used in the V&V study. Appendix B presents a compilation of publications that have applied the CMS wave or flow models independently or together for an integrated wave, flow, and sediment transport study. For some of these studies, the precursor to the CMS's flow model, CMS-M2D, was applied. Other studies coupled the CMS with external circulation, wave, and/or sediment transport models, as noted. The purpose of the annotated bibliography is to provide the reader references for more detailed investigation into the types of CMS applications that have been conducted in the past. Each application and the problem that was addressed are described in Appendix B, followed by a reference publication. Discussions are organized alphabetically by the reference. All references are available from the CIRP website under "Publications."

2 Strategy and Plan for CMS V&V Study

2.1 Overview of the Coastal Modeling System (CMS)

CMS is an integrated two- and three-dimensional (2-D and 3-D) numerical modeling package for simulating waves, current, water level, sediment transport, and morphology change at coastal inlets and entrances. The emphasis of the CMS is on navigation channel performance and sediment exchange between the inlet and adjacent beaches. The CIRP is developing, testing, and transferring the CMS to Corps Districts and industry for use on specific engineering studies. Some key features of the CMS are:

- Versatile graphical user interface with many utilities available
  The CMS runs within the Surface-water Modeling System (SMS) versions 8.2 and higher.
- Two options for coupling the wave and flow models
  - Inline code
    - CMS is available with the wave and flow models in one code, called the "inline" code.
    - The inline code includes internal coupling (steering) for faster and more efficient simulations.
  - Coupling or steering
    CMS-Wave and CMS-Flow can also be run in a coupled or steering mode within SMS, with information passed between the models at user-specified intervals.
- Two solution schemes
  - Implicit solution
    - An option to run the implicit solution scheme allows larger time steps (on the order of 10 min) as compared to the explicit version of the code.
    - The implicit solution results in shorter simulation times (for tidal flow and morphology change).
  - Explicit solution
    The explicit solution scheme allows more accurate calculation of processes that occur on orders of seconds to minutes, such as runup, overtopping, transmission through jetties, and barrier island breaching.
- Two grid options
  - Cartesian (constant or varying square/rectangular) grid

Simple to setup for rapid evaluations of alternatives
- Quad-tree (telescoping) grid
  - Facilitates local refinement through cell division of the rectangular grid
  - Flexible and efficient simulations
- Option for constant or spatially variable wind and atmospheric pressure
  Users can apply spatially-varying or constant winds and atmospheric pressure at boundaries of the grid.
- Wave-current interaction options
- Stable treatment of water level/velocity boundary conditions
- Hard bottom algorithm option with an adjustable layer thickness for controlling capacity and stability
- Additional grid modification capabilities in SMS

The overall framework of the CMS is depicted in Figure 1:

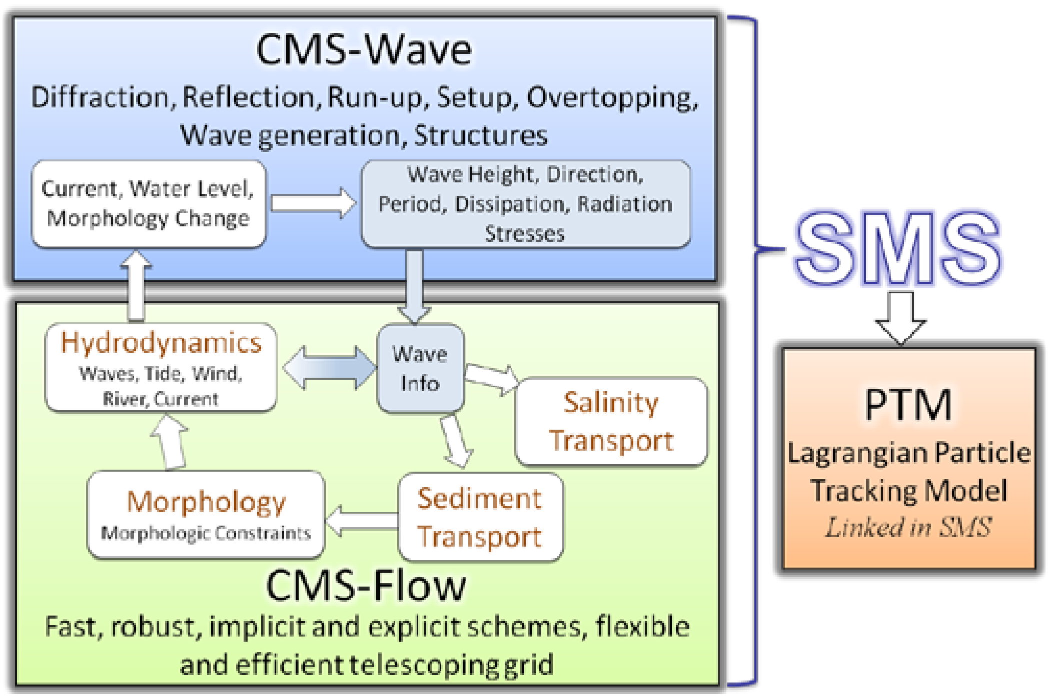

Figure 1. CMS framework and its components.

Two major components of CMS are the wave (CMS-Wave) and hydrodynamics (CMS-Flow) models. The sediment transport and morphology change is included in the CMS-Flow (e.g., it is not a separate model). The CMS also can force the Particle Tracking Model (PTM) within SMS, which is

shown in Figure 1 for completeness but not evaluated in this V&V study. A brief description of the CMS components follows.

The CMS-Wave is a spectral wave transformation model and solves the steady-state wave-action balance equation on a non-uniform Cartesian grid. It considers wind wave generation and growth, diffraction, reflection, dissipation due to bottom friction, white-capping and breaking, wave-current interaction, wave runup, wave setup, and wave transmission through structures. The V&V Report 2 has detailed information about the model features, its V&V evaluation and types of applications, and performance skills. Additional information about CMS-Wave is available from the CIRP website: http://cirp.usace.army.mil/wiki/CMS-Wave.

CMS-Flow is a coupled hydrodynamic and sediment transport model capable of simulating depth-averaged circulation, salinity and sediment transport due to tides, wind and waves, and the resulting morphology change. The hydrodynamic model solves the conservative form of the shallow water equations and includes terms for the Coriolis force, wind stress, wave stress, bottom stress, vegetation flow drag, bottom friction, wave roller, and turbulent diffusion. There are three sediment transport models available in CMS; a sediment mass balance model, an equilibrium advection diffusion model, and a non-equilibrium advection-diffusion model. Depth-averaged salinity transport is simulated with the standard advection diffusion model and includes evaporation and precipitation. All equations are solved using the Finite volume method on a non-uniform Cartesian grid. Finite volume methods are a class of discretization schemes that have proven highly successful in approximating the solution of a wide variety of conservation law systems. They are used extensively in fluid mechanics, porous media flow, meteorology, modeling biological processes, and many other engineering areas governed by conservative systems that can be written in integral control volume form. Finite-volume formulation can be implemented either in finite-difference or finite-element (unstructured grid) for solving the governing equations of coastal wave, flow and sediment transport models. The V&V Reports 3 and 4 describe the hydrodynamic (Report 3) and sediment transport and morphology change (Report 4) aspects of this model, the V&V evaluations, applications, and associated performance skills. Additional information about CMS-Flow is available from the CIRP website: http://cirp.usace.army.mil/wiki/CMS-Flow.

The CMS package consists of a suite of numerical models designed for simulating flows, waves, sediment transport, and morphology changes taking place nearshore in the coastal region. The system is designed specifically for navigation projects dealing with channel design and performance requirements, and sediment management issues in coastal inlets and adjacent beaches. As such, CMS assists the Corps to improve the use of USACE O&M funds. The CMS is designed for Districts to use on desk-top computers, and it takes advantage of the SMS interface for grid generation and model setup, as well as plotting and post-processing.

2.2 Outline of the V&V process

2.2.1 Background

The fundamentals of a generic numerical model V&V process are described in this section. A short summary is given here, and additional information about specifics of the process is available from related publications listed in the References section of this report (e.g., AIAA 1998; ASCE 2008; Bobbit 1988; Lynch and Gray 1978; Lynch and Davies 1995; Oberkampf and Trucano 2002; Oreskes et al. 1994; Roache 1989, 1997, 1998, 1999; Trucano et al. 2003; Wang 1994). In engineering, there are two types of model evaluations: verification or validation. V&V are two different technical terms, each with a specific purpose; however, these words are often used interchangeably in the engineering realm. Definitions of these terms and a description of the relationship between the two are provided.

The V&V process has gained an increasing attention in the last two decades because of a requirement that numerical models must be evaluated rigorously for them to become accepted and certified in engineering practice (ASCE 2008; Oberkampf and Trucano 2002; Roache 1999). The V&V process helps to develop problem-specific user guidance for future applications of models and also assist model developers to identify future R&D needs to improve models.

The governing equations and prescribed boundary conditions of the CMS system of models are complex. These are also closely tied to the user-controlled input parameters, some of which are unknown or contain inherent errors. These complex models in coastal engineering applications are expected to produce reliable estimates. In applications, this assessment is based on an acceptable agreement between model predictions and data.

The performance of models must be robust and the physics reliably reproduced consistently regardless of different sites or conditions. These are high expectations which demand that all capabilities of the CMS be confirmed before they are used in District projects. As noted, the CMS package consists of a set of numerical models which involve:

1. Adapting partial differential equations with initial and boundary conditions;
2. Developing mathematical algorithms for the numerical solution of equations;
3. Implementing these algorithms in a computer software package;
4. Executing the code on personal computers; and
5. Analyzing the results produced by the modeling system.

Consequently, the correct implementation of the above five requirements in the CMS model codes is paramount because all influence the model's results. Each of these concerns has been addressed in this V&V study.

2.2.2 Purpose

This V&V study is performed to ensure the CMS is ready for real world applications because the modeling codes include a complex system of equations and boundary conditions which require specification of a set of input parameters. The governing equations of the CMS models are solved both with explicit and implicit solvers in a finite difference scheme. This V&V study helps the CIRP to determine if:

1. The CMS has the right capabilities;
2. The overall system is mathematically correct and functioning as it should;
3. The code numerics are robust; and
4. Model solutions are consistent and convergent.

These performance criteria are achieved by testing the computational capabilities of the CMS models carefully, and calibrating and validating properly the individual models and then the integrated system of models with a large number of analytical solutions and data. The errors in the modeling estimates are quantified in this V&V study. All this useful information is essential to field applications of the CMS, which will also serve as guidelines to users in District projects. For clarity, we define some key terms which have been used throughout this V&V study and its reports. The basic V&V approach, process and terminology used for the

CMS V&V follow the outline of the American Society of Civil Engineers' (ASCE 2008) V&V protocol closely.

2.2.3 Definition of terms

Code is the software that implements the solution algorithms in step (3) above. In other words, a computer code here refers to the software implementation component of a numerical model.

Verification is the process of determining that a model implementation represents the developer's conceptual description of the model and its solution accurately. It is the process of confirming that a computer code implements the algorithms that were intended correctly. As such, verification tries to answer a few fundamental questions about a numerical model (e.g., AIAA 1998; ASCE 2008; Oberkampf and Trucano 2002; Oreskes et al. 1994; Roache 1989, 1997, 1998, 1999; Trucano et al. 2003):

- Are the right equations used;
- Are the governing equations implemented correctly, solved properly and accurately;
- Does the solution converge?

Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of a model. It is the process of confirming that the predictions of a code represent measured physical phenomena adequately. As such, validation is intended to answer one very important question: do the governing equations accurately represent field data from a prototype environment (called site validation) or data obtained from a scaled environment in physical model studies? Additional information on verification and validation in computational science and engineering is available in the published literature (e.g., AIAA 1998; ASCE 2008; Bobbit 1988; Lynch and Davies 1995; Oberkampf and Trucano 2002; Oreskes et al. 1994; Roache 1998, 1999; Trucano et al. 2003; Wang 1994).

Calibration of models is another term that is sometimes confused with verification and validation. Calibration means tuning model coefficients to reproduce a measured or understood response. Validation follows calibration without changing the model's coefficients or setup to reproduce additional measurements or known behavior for a wide range of site-specific inputs and conditions. Occasionally, the term model calibration is

used when testing is conducted for a set of code input parameters associated with calculations prior to validation (e.g., AIAA 1998; ASCE 2008; Oberkampf and Trucano 2002; Oreskes et al. 1994).

The code output is referred to either as *predictions, results, calculations,* or *estimates,* which are model's output obtained for a specific input set used to run the code.

Given the above definitions and recent guidelines provided in the ASCE (2008), four observations are made:

1. Both calibration and validation depend on results of verification;
2. Calibration and validation cannot use the same data set;
3. Validation is dependent on the results of calibration; and
4. Calibration is not a substitute for validation in engineering applications.

The above stated distinctions between Verification and Validation are important to understanding, interpretation, and application of the work presented in this and the three companion reports. Technically, achieving complete verification and validation of numerical models of coastal systems is enormously difficult, if not impossible, because coastal modeling systems are multi-faceted, process-driven, sensitive to inputs used, and modeling results are not unique. The results provided in this and the companion V&V reports are based on the best application of the CMS by experts and their calibration of models with the available engineering data.

The process to evaluate the CMS general skills for coastal engineering applications started with the verification of its mathematical and computational capabilities, followed by a systematic and thorough checking, calibration, and validation with analytical solutions and data. This overall process is termed here as a V&V study for the CMS, a rather rigorous and systematic process, and the fundamentals of it are described earlier in this chapter. Details of the V&V execution are described in Reports 2, 3, and 4.

2.2.4 V&V study plan

The V&V study for the CMS was executed by employing three categories of information sources:

1. Verification with analytical/empirical solutions (Category 1);
2. Validation with data from laboratory experiments (Category 2); and
3. Validation with data from field studies (Category 3).

Test examples chosen for each category included some known analytical solutions, idealized problems, or laboratory studies and field studies with data. A large number of test cases were identified to be appropriate for evaluating the different capabilities of the CMS. Work is in progress on additional test cases. Only a finite number of test cases have been completed in each category, and these are included in Reports 2, 3, and 4. The evaluation of the CMS with the remaining test cases will be included in future updates and other related publications. Table 1 summarizes the complete set of cases evaluated and documented in Reports 2, 3, and 4.

Table 1. Comprehensive list of V&V tests cases identified for the CMS.

V&V Test Cases for CMS-Wave			
Processes Involved	**Analytical/Empirical Solutions (Category 1)**	**Laboratory studies with data (Category 2)**	**Field Applications with data (Category 3)**
Wind-wave generation Propagation in half plane Propagation in full-plane	CEM/SPM curves (for wave generation and growth over short, long and fetch-limited distances)	no studies known	Matagorda Bay, TX Mouth of Columbia River, WA/OR Mississippi Sound, MS Indian River County, FL
Wave-wave interaction Infragravity waves	JONSWAP*	No studies known	Mouth of Columbia River, WA/OR
Wave breaking formulas Wave-current interaction	Limited studies*	Idealized Inlet Visser (1991)	Duck, NC (FRF) Mouth of Columbia River, WA/OR Grays Harbor, WA Matagorda Bay, TX Southeast Oahu, HI
Wave diffraction Wave reflection	CEM/SPM diffraction curves (gap problem)	No studies known	Grays Harbor, WA
Wave-structure interaction (Runup, transmission, overtopping)	Limited studies*	Mase & Iwagaki (1984); Ahrens &Titus (1981) Cleveland Harbor Lab study.	Mouth of Columbia River, WA/OR Grays Harbor, WA
V&V Test Cases for CMS-Flow: Hydrodynamics			
Processes Involved	**Analytical/Empirical Solutions (Category 1)**	**Laboratory studies with data (Category 2)**	**Field Applications with data (Category 3)**
Tidal Currents and Water Levels	Tidal propagation in quarter annulus Transcritical flow over a bump Long-wave runup over a frictionless slope	Steady flow with spur dike Steady flow with sudden expansion	Gironde Estuary, France Grays Harbor, WA Ocean Beach, CA St. Augustine Inlet, FL Shark River Inlet, NJ East Harbor, MA

Wind-Driven Currents	Wind-driven flow in circular basin Wind setup in flat basin	no studies known	Houston-Galveston, TX Matagorda Ship Channel, TX
2-Dimensional Salinity	no studies known	no studies known	Matagorda Bay, TX
Wave-Current Interaction	no studies known	Longshore current induced by regular waves (LSTF) Wave-induced current near an idealized inlet	Ship Island, MS Ocean Beach, CA Duck, NC (DELILAH) Hazaki Research Facility, Japan
V&V Test Cases for CMS-Flow: Sediment Transport and Morphology Change			
Processes Involved	**Analytical/Empirical Solutions (Category 1)**	**Laboratory studies with data (Category 2)**	**Field Applications with data (Category 3)**
Advection-Diffusion	Scalar transport in idealized channel with advection; with advection & diffusion	no studies known	no studies known
Channel Infilling	no studies known	Channel infilling and migration: steady flow; waves parallel to flow; waves perpendicular to flow	Shark River Inlet, NJ
Ebb/Flood Shoal Morphology Change	no studies known	no studies known	St. Augustine Inlet, FL
Longshore Sediment Transport and Nearshore morphology change	*	Large-scale Sediment Transport Facility	Ocean Beach, CA Shark River Inlet, NJ Shinnecock Inlet, NY
Cross-shore Processes (Surf Zone) Berms, Sand Bars, Swash Bars	*	*	*
Swash Zone Processes (Shoreline Change)	no studies known	Large-scale Sediment Transport Facility	*
Nonuniform Transport (Mixed Sediments)	no studies known	Deposition of nonuniform sediments	Shark River Inlet, NJ St. Augustine Inlet, FL Grays Harbor, WA
Structures & Hardbottom	no studies known	Clear water jet erosion over hard bottom	*

*Additional case studies to be evaluated in future V&V applications.

In the remainder of this report, we provide a summary of the CMS V&V study that has been performed using the above test cases. Details of each test case are presented in its corresponding V&V study report, and these are not duplicated here. Instead, a summary of each test case is provided. The summary is organized as follows:

- Chapter 3 for waves (CMS-Wave, Report 2),
- Chapter 4 for hydrodynamics (CMS-Flow, Report 3), and

- Chapter 5 for sediment transport and morphology change (CMS-Flow, Report 4).

Within each chapter, the analytical, laboratory, and field cases are grouped into the three categories as shown on Table 1. Each test case is summarized by a problem description and major findings. These are rather short for the Category 1 test cases, but comparatively longer for laboratory and even much longer for the field data validation cases, which are rather complex and provide additional information for project applications. Chapter 6 provides a summary and recommendations.

3 Summary of V&V Study for CMS-Wave (Report 2)

3.1 Introduction

CMS-Wave calculations were verified with published analytical solutions and empirical relationships for a defined range of conditions (Category 1 test cases). The purpose of these verification applications was to ensure that the numerical implementation of the relationships being calculated in the CMS-Wave were implemented correctly and converged to the proper solution. Neither the mere similarity nor even a full agreement between numerical and analytical solutions guarantees the correspondence of either one to reality (prototype). A numerical solution verified in the realm of an analytical solution cannot be considered verified beyond the range and realm of the analytical solution. Therefore, following the analytical verification, more rigorous laboratory and field cases were required to validate the model. Category 2 includes test cases with data from laboratory experiments (physical modeling studies). Category 3 includes real cases with data from field studies (prototype experiments).

3.2 Category 1 test cases: Analytical and empirical solutions of idealized problems

The analytical or empirical solutions of several idealized test cases are selected in the verification of the CMS-Wave to confirm that the intended numerical algorithms have been implemented correctly in the model. Each test case has a tagged ID, with the first two characters identifying the category number, followed by a dash and the example number in that category. For example, the test case C1-Ex1 refers to Category 1 - Example 1. This notation is used henceforth. These tests represent some simple and idealized mathematical problems with analytical or empirical solutions. As stated in the description of the V&V process, the solutions of these test cases are important to verify the CMS-Wave calculations. These comparisons demonstrate that CMS-Wave implementation represents the conceptual description of the model and results are accurate mathematically and reliable. In other words, the verification is performed to verify correct implementation of computational methods and solution schemes in CMS-Wave as intended.

The following tests were performed:

1. Wave generation and growth for limited fetch condition,
2. Wave-wave interactions in spectral wave transformation,
3. Wave diffraction through a breakwater gap.

Cases in progress:

1. Wave-wave interaction in deep and shallow water,
2. Wave dissipation over a muddy bottom.

3.2.1 Test C1-Ex1: Wave generation and growth in limited fetch

Description: The purpose of this test was to compare the CMS-Wave calculation of wave generation and growth curves for fully-developed seas to the method given in the Shore Protection Manual (*SPM* 1984) under the fetch-limited condition. The wave generation and growth curves (see SPM 1984, Equations 3-33 through 3-38 and Figures 3-22 through 3-24) are based on the Sverdrup-Munk-Bretschneider (SMB) method, developed originally in the 1950s for deepwater wave growth and forecasting. The SMB diagram shown in the SPM has improved the empirical equation for shallow-water constant depth applications. Additional depth and fetch applications are considered under the Category 3 test cases (field validations).

Findings: CMS-Wave simulations were performed for low, moderate, and strong wind speeds, and for fetch lengths from 0 to 20 km. Wave height and wave period calculations from CMS agreed with the SMB curves given in the SPM (1984), with differences less than 10 percent for fetch length greater than 5 km. This test verified that CMS-Wave can be applied for wave generation and growth in the coastal and estuary area with fetches greater than 5 km. Future tests in this category will consider shorter and longer fetches as well as different wind speeds and water depths.

3.2.2 Test C1-Ex2: Wave-wave interactions in spectral wave transformation

Description: The purpose of this test was to compare CMS-Wave calculated nonlinear wave-wave interactions to an analytical solution given by Jenkins and Phillips (2001) to assess the model’s ability to represent redistribution of wave energy and change in the spectral shape resulting

from these interactions. These interactions give rise to a redistribution of wave energy, which causes the wave spectral shape to change. Jenkins and Phillips (2001) have proposed a simplified formulation to represent nonlinear wave-wave interactions as a second-order diffusion operator that conserves wave energy and wave action. Because their formulation is independent of the dispersion relation, it is applicable in both deep and shallow water. The Jenkins and Phillips (2001) formulation has been extended to both deep and shallow waters, and implemented in the wave-action balance equation to calculate nonlinear wave-wave interactions efficiently (Lin et al. 2010).

Findings: In this idealized test case, CMS-Wave represented efficiently the frequency increases and decreases (up- and down-shifting processes) and corresponding wave energy re-distribution associated with nonlinear wave-wave interactions. Other nonlinear models are usually computationally extremely demanding and cannot be used on desktop machines. The approximation implemented in CMS-Wave is intended to address this important need in practical applications. Lin et al. (2010) have conducted additional tests to demonstrate that the nonlinear wave-wave interaction is more significant in the large coastal domain from deep to shallow water under strong wind conditions. Future tests will evaluate the capability for large domains, different water depths, and large wind wave conditions. In particular, more tests are needed to determine the applicability of the extended formulation to shallow depths and different fetch applications.

3.2.3 Test C1-Ex3: Wave diffraction at breakwater gap

Description: The purpose of this test was to compare CMS-Wave calculations to wave diffraction diagrams in the Coastal Engineering Manual (CEM 2006, see Figures II-7-7 through II-7-17) and the Shore Protection Manual (SPM 1984, see Figures 2-40 through 2-59), based upon the Sommerfeld solution at breakwater gaps. The wave diffraction diagrams were compiled originally by Wiegel (1962) for a straight semi-infinite long breakwater and by Johnson (1952) for a breakwater gap for monochromatic incident waves impinging on these structures from different directions.

Findings: CMS-Wave simulation were performed for a gap of a width B = 0, L and $2L$ (L = wavelength) and constant depth. In these simulations, the entire incident wave energy was placed in one frequency and direction bin to represent monochromatic waves. Model predictions replicated the analytical solutions closely, with the best agreement in the strong diffraction

zone (0 to L distance down-wave of the gap); as waves propagated further from the gap, the difference between model-analytical solutions increased gradually. CMS-Wave can calculate wave diffraction for engineering practice in feasibility level studies and preliminary works. If a greater accuracy is required in applications, a phase-resolving wave model such as CGWAVE, a Mild-Slope Equation model (Demirbilek and Panchang 1998), BOUSS-2D, a Boussinesq model (Nwogu and Demirbilek 2001), or a physical model study could be used.

3.3 Laboratory studies with data (Category 2 test cases)

The test cases under Category 2 include studies with data from various physical modeling studies conducted worldwide. The completed and remaining cases are listed below, and the latter cases are under investigation and will be included in future reports.

Completed cases:

1. Smith et al. (1998) idealized inlet experiments. Test for wave breaking on a current at an inlet.
2. Visser (1991) experiments. Test for wave breaking on a planar beach.
3. Ahrens and Titus (1981), Ahrens and Heimbaugh (1988), Mase and Iwagaki (1984), and Mase (1989) experiments. Tests for wave runup over sloping structures.
4. Bottin (1983) wave propagation into Cleveland Harbor, Ohio. Test for wave shoaling, refraction, diffraction, wave-current interaction, and wave transmission over breakwaters.

Cases in progress:

1. Chawla and Kirby (2002) experiments. Test for wave breaking.
2. Seabergh et al. (2002, 2005) the CIRP idealized inlet physical model experiments.
3. Smith (2011) LSTF experiments for waves over artificial reef and offshore bar migration.
4. Demirbilek et al. (2007b) University of Michigan experiments for wave runup over a reef.
5. Hamilton and Ebersole (2001) LSTF experiments for wave-induced longshore currents.

Three statistical measures described in Appendix A are used for the "goodness-of -fit" error metrics to characterize the level of agreement obtained between the model and data. These are the Root-Mean-Square Error (RMSE), Correlation Coefficient (R) or Coefficient of Determination (R^2), and Mean Absolute Error (MAE). Mathematical definition and description of these statistical error metrics is provided in Appendix A and a few V&V publications which are listed in References.

3.3.1 Test C2-Ex1: CHL idealized inlet experiments

Description: Smith et al. (1998) conducted a laboratory experiment to investigate wave-current interaction and associated wave breaking in an idealized entrance with dual jetties. Details of this experiment are given in that study report. In summary, the physical model included a steep beach with wave and current meters deployed for measurements in the vicinity of the channel, jetties, and nearshore. The dual jetties had a spacing of 3.7 m and extended 5.5 m offshore, to protect the entrance channel where the depth varied from 9 cm to 12.8 cm. The inlet throat converged to a depth of 15.2 cm. Twelve wave/current conditions were tested (Runs 1 through 12), covering a wide range of wave and current parameters. In the experiment, Runs 1 to 4 were without a current, and Runs 5 to 8 had a moderate steady-state ebb (offshore) current of approximately 11 cm/sec at the inlet entrance. Runs 9 to 12 had a strong steady-state ebb current of approximately 22 cm/sec at the entrance. All incident waves were generated in the basin (perpendicular to the shoreline) with a unidirectional plunge-type generator. Wave data were collected along one transect line in front of the wave maker and three shore-normal transect lines in the entrance channel.

Findings: For the case without current, good model-data comparison (less than 15 percent difference) for wave heights was obtained with four wave breaking formulas implemented in CMS-Wave. The values of MAE were nearly the same for all of these formulas but overall, the Extended Goda formula produced the smallest error (MAE and RMSE) while Miche's formula resulted in the largest error. Runs 1 and 3, with larger incident wave heights, had the largest errors.

For the longer incident wave period with an ebb current, good agreement (less than 15 percent RMSE) was obtained both for large and small wave heights and current magnitudes with all four breaking formulations. For the shorter period wave conditions, both Battjes and Janssen (1978) and the Extended Miche formulas overestimated the wave height, while the

Chawla and Kirby (2002) and the Extended Goda formulas yielded similar estimates of wave height. Overall, for these wave-current interaction tests, the Battjes and Janssen (1978) formula consistently performed about 10 percent better on average than all other wave breaking formulas. Therefore, the Battjes and Janssen (1978) wave breaking formula is recommended for wave-current interaction problems at inlet applications, and also for cases without currents. The Extended Goda formula can also be used in applications with no currents.

3.3.2 Test C2-Ex2: Wave breaking experiments on a planar beach

Description: Visser (1991) conducted eight laboratory experiments (labeled Exp. 1 to Exp. 8, which are denoted here as Runs 1 through 8) to generate a longshore current with monochromatic incident waves breaking on a planar beach. Wave, current, and water level data were collected for a number of incident wave conditions tested for two beach slopes (1:10 and 1:20) and two different bottom roughnesses. Although these experiments used monochromatic waves (e.g., no irregular wave tests were performed), the data are fundamental for checking wave and flow models for wave refraction, shoaling, breaking, and wave-induced currents. Lin et al. (2008, 2011) provided additional analysis of these experiments with wave and flow models for all Runs. Here, only Runs 4 to 7 were selected for model validation because these tests had the same bottom composite slopes and the most complete set of measurements. The beach had a 1:10 slope for the first seaward 1-m distance, 1:20 slope for the next 5-m distance, and a flat bottom for the next 5.9 m to the wave generator. Runs 4 through 6 were conducted on a concrete bed, where the bottom friction is expected to be small and, therefore, were neglected in the numerical wave simulation. In Run 7, the 1:20 slope bottom was roughened by a thin layer (0.5 cm to 1.0 cm) of gravel grouted on the concrete floor.

Findings: For oblique monochromatic waves breaking on a planar beach and interacting with the longshore current, the calculated wave heights agreed with data for all four wave breaking formulas in CMS-Wave. The largest error in the calculated wave height was less than 5 percent of the incident wave height along a planar beach. While these results are for monochromatic waves, other test cases provided under Categories 2 and 3 include applications with irregular waves. Therefore, this test case was necessary for validation of the wave model, to show that CMS-Wave represents wave refraction, shoaling, breaking, and wave-induced currents accurately.

3.3.3 Test C2-Ex3: Wave runup on impermeable uniform slope

Description: The purpose of this test case was to validate the wave runup calculation in CMS-Wave with two datasets for a uniform slope. Two laboratory experiments (Ahrens and Titus 1981; Mase and Iwagaki 1984), supplied the data for this validation. Detailed information on measurements, including dimensions of the flume, gauge types, and data analyses performed are all available from these references. Random incident waves were generated in both experiments in a wave flume consisting of a flat bottom offshore of a sloping beach. The experiments by Ahrens and Titus included 275 wave conditions (Ahrens and Heimbaugh 1988), with the significant wave heights ranging from 4 cm to 20 cm, spectral peak periods from 1.1 sec to 4.5 sec, and six uniform slopes (1:1, 2:3, 1:2, 2:5, 1:3, and 1:4). The experiments by Mase and Iwagaki (1984) used 120 wave conditions (Mase 1989), with significant wave heights ranging from 2.7 cm to 11 cm, spectral peak periods from 0.8 sec to 2.5 sec, and four uniform slopes (1:5, 1:10, 1:20, and 1:30).

Findings: The calculated two percent exceedence wave runup ($R_{2\%}$) showed higher correlation with data for flatter slopes (1:5 to 1:30) than the steeper slopes (1:5 to 1:1). This is expected because runup distance is less over flatter slopes, which decreases the margin for error. It was concluded that the CMS-Wave runup function can be applied to coastal structures and beaches with the seaward slope less than 1:5 (gentler slopes), and can be used for preliminary estimates of wave runup in projects. For steep slopes, estimates of wave runup may require using phase-resolving nonlinear models or physical modeling studies.

3.3.4 Test C2-Ex4: Experiments for Cleveland Harbor, Ohio

Description: The purpose of this test was two-fold:

- Compare CMS-Wave calculations to data from a physical modeling study that investigated wave propagation at the entrance of Cleveland Harbor; and
- Inform users about a recent CMS-Wave model verification and validation study (Demirbilek et al. 2010) that provided wave estimates in and around the Cleveland Harbor complex in support of planned harbor modification works.

A 1:100-scale physical model of Cleveland Harbor, Ohio, was constructed in 1980-1981 at the Waterways Experiment Station (WES) to investigate the effects of waves, currents, and river flow on ship maneuverability (Bottin 1983). The laboratory experiment tested 126 cases, consisting of 20 incident wave heights, 12 wave periods, 3 wave directions, 3 lake water levels, and two river discharges. Twenty-nine wave gauges in the harbor main entrance and interior of harbor measured wave heights in the physical model.

Findings: Wave heights calculated with CMS-Wave compared reasonably well to data from the Cleveland Harbor physical model, with some large errors as much as 50 percent in some cases for certain wave conditions and gauge locations. The best agreement was for higher waves outside the entrance to the harbor. Inclusion of bottom friction and infragravity effects had minimal effects on model-data comparison, suggesting that in this test case the dominant wave processes were wave diffraction, reflection, wave transmission/overtopping of structures, entrance losses (not represented in CMS-Wave), and wave-current interaction. The calculated waves inside the harbor complex were generally slightly overpredicted, suggesting that there was too much wave transmission and/or overtopping considered in the simulations. No attempt was made to calibrate the model to data, and the model was run with default parameters to objectively evaluate its suitability for these types of applications.

Overall, in spite of numerous differences in the bathymetry and changes in the harbor geometry and structures, and input conditions between numerical and physical model studies, the predictions and data exhibited similar trends. The overall model-data comparison was satisfactory. Quantitatively, the model results were similar to laboratory data, but wave heights predicted by CMS-Wave decayed through the entrance faster than waves in the laboratory study. The comparison also showed that waves near the piers at the Cuyahoga River mouth outside the entrance were similar to the CMS-Wave result. Comparison of model and CEM diffraction diagrams for a gap problem (discussed in Case C1-Ex3) was also performed to further evaluate the model's diffraction estimates (Demirbilek et al. 2010). This comparison is omitted here since model results were verified for a gap problem in Chapter 1 and interested readers can find details in these references.

For harbor applications, CMS-Wave simulations should include all processes and interactions of significance such as wave diffraction,

reflection, transmission, overtopping breakwaters, wave-current interaction, and infragravity wave effects. Because it is not possible to isolate the individual importance of each of these processes, this test case validated nearshore wave heights calculated by CMS-Wave at the Cleveland Harbor entrance, to demonstrate that the model is suitable for these types of engineering applications. Given this is an “extreme” application for a spectral wave model (because strong reflection, diffraction, runup / overtopping, and wave-current interactions are challenging for this class of wave models), the test case shows that the model is appropriate for planning and feasibility level studies. Final design estimates for these complex applications should be checked with phase-resolving wave models (e.g., CGWAVE or BOUSS-2D), which need the transformed wave conditions from the CMS-Wave offshore of the harbor complex.

3.4 Field applications with data (Category 3 test cases for CMS-Wave)

The Category 3 test cases represent applications of CMS-Wave to projects (field studies) containing measured data. The completed cases are summarized in this section, while the in-progress (under study) cases will be presented in a future companion report. As indicated earlier, a more comprehensive summary for each test case is provided for Category 3 cases, so that users can receive guidance for field applications of the CMS-Wave model.

Completed cases:

1. Matagorda Bay, TX
2. Grays Harbor, WA
3. Mouth of the Columbia River, OR/WA
4. Southeast Oahu coast, HI
5. Recent Field Research Facility (FRF), NC, wave measurements
6. Mississippi Coastal Improvement Program (MsCIP), and
7. Indian River County, FL

Cases in progress:

1. Pillar Point Harbor, CA
2. Noyo Harbor, CA
3. Galveston Bay, TX

For all field test cases investigated, the bottom friction was included in the CMS-Wave simulations. The recommended default value for sandy beds is $C_f = 0.005$ for the Darcy-Weisbach coefficient, and $n = 0.025$ for the equivalent Manning's coefficient.

3.4.1 Test C3-Ex1: Matagorda Bay, TX

Description: The purpose of this test case was to verify local wind-wave generation in half-plane and full-plane capabilities of the CMS-Wave for calculating wave heights in an enclosed bay that is connected to an inter-coastal waterway (ICW), as well as to a major water body (Gulf of Mexico). Matagorda Bay is located on the south central coast of Texas, with a surface area of approximately 930 km^2 and quite shallow depths ranging between 2 to 4 m. The tidal prism is large because of vast bay surface area, despite the modest tidal range of only 0.33 m in the bay. The bay is separated from the Gulf of Mexico by Matagorda Island and Matagorda Peninsula. Freshwater discharge that originates from the Colorado River and the Lavaca River is less than 10 percent of the daily tidal exchange through the two coastal inlets with the Gulf of Mexico. Local wind is the dominant forcing for wave generation in the bay.

Directional wave spectra and water level data were collected with a bottom-mounted Acoustic Doppler Profiler (ADP) in 3.8 m of water for the time period from September - December 2005, at a middle bay location (Puckette 2006). Local wind and tide data were available from a NOAA Station 87737011 at Port O'Connor in the southwest corner of the bay. The hourly wind, tide, and wave data collected in September-December 2005 were used in this validation. Water level data collected at MBWAV and Port O'Connor show that the spatial variations of water level in the bay occur under the passage of a cold front system and strong winds. The strong wind condition on 24 September 2005 was Hurricane Rita.

Findings: CMS-Wave was able to model the generation and propagation of wind-waves for relatively high wind speeds in this shallow bay region. The calculated wave parameters were similar to the measurements for the four largest storm events during the 3 month measurement period, although there are some significant differences between the measured and the calculated wave direction and period. The calculated spectral peak wave period was slightly underestimated, probably because the nonlinear wave energy transfer is more pronounced in the shallow water than in deep water and would be difficult to model accurately in this shallow

basin. Presence of large amounts of fine sediments and mud aggregates in the bay were not considered in the simulations, which can affect the accuracy of calculated wave parameters. For this case with high wind speeds and shallow water depths, CMS-Wave was able to model the wind-waves with a RMS error of 0.1 m in height (~25 percent) and 0.5 sec in period (~25 percent). Errors in wave direction were large, and are likely related to the difficulty in measuring wave direction in low wave environments accurately.

In general, wave calculations in a shallow basin are controlled by wind forcing and energy loss due to white capping. This test case demonstrated that it is more efficient (twice as fast) to run the CMS-Wave in a half-plane mode in a bay or lake-alone application. In the case of a bay or estuary interacting with a sea through inlets/exits, it would be necessary to run the CMS-Wave in a full-plane mode.

3.4.2 Test C3-Ex2: Grays Harbor, WA

Description: The purpose of this test case was to evaluate the combined wind and wave modeling capabilities of CMS-Wave in a large tidally-dominated inlet environment with an energetic wave climate. Extensive field data were collected in 1999, 2003 and 2005, including wave and current measurements for Half Moon Bay (HMB), a region in the lee of the south jetty; in the navigation channel; north side of the channel; and back in the estuary, which make this a good test for a wave model.

Grays Harbor (GH), located on the coast of southwest Washington, is one of the largest estuaries in the continental United States. The spring tidal prism reaches 570 million m^3 corresponding to the surface area of 200 km^2 at mean tide level, with a tidal range of 2.8 m. The entrance to GH experiences extreme northwest Pacific waves during winter, and significant wave heights commonly exceed 6 m during winter storms. The entrance, protected by two rubble-mound jetties, is approximately 2 km wide, and a deep-draft navigation channel is maintained at 12 m to 13 m relative to mean low lower water. Strong ebb currents that exist between the jetties can increase wave height by as much as 0.5 m to 1.5 m as observed in the inlet entrance.

Strong wave refraction and diffraction at the eastern end of the south jetty contribute to increased beach erosion in HMB, which is adjacent to the landward terminus of the south jetty and has a spiral bay-type of

shoreline. To examine the influence of waves and currents in HMB, wave and current data were collected at four stations between December 2003 and February 2004. Osborne and Davies (2004) provided details of instrumentation used and data collection and analyses. During the same time interval, offshore wave information was available from a Coastal Data Information Program (CDIP) Buoy 036 in a water depth of 40 m (relative to Mean Tide Level, MTL) and from the National Data Buoy Center (NDBC) Buoy 46029, located approximately 100 km south-southeast of Grays Harbor. Ocean surface wind measurements were also available from Buoy 46029 (50 km west of Mouth of the Columbia River). A winter storm occurred during 24-28 December 2003 with the largest offshore measured wave height exceeding 6 m. The simulations for the period of 10-30 December 2003 and this storm event were used in model validation.

Findings: The trends in CMS-Wave calculations followed the data, with some differences in the wave height, wave period, and direction. Calculated wave results improved with coupled simulations of CMS-Wave and CMS-Flow because processes in the area of interest are affected by the combination of waves and current. The effect of shallower water on waves was evident in the comparison of calculated results with data at stations in the lee of the jetty and closer to the HMB shoreline. The effect of current was more evident at stations located in relatively deep water closer to the navigation channel. Results indicated that CMS-Wave calculated wave height more accurately closer to the navigation channel in relatively deep water (4 m to 8 m). The model results were less satisfactory in a sheltered area where wave diffraction, reflection, refraction, shoaling, and breaking in the shallow water (~2-m depth) are stronger as compared to measurements in the channel. The results suggest that these mechanisms are not modeled optimally.

Overall, CMS-Wave performed reasonably well for this extremely dynamic and challenging field site. Because modeling estimates for a given study would depend on wind, wave, tide, and bathymetric inputs, a sensitivity study should be conducted to determine the best input parameters in future testing and project applications. For applications to jettied inlets with longer incident waves, the role of infragravity waves, nonlinear wave-wave interactions, and wave transmission and overtopping of breakwaters should be considered in CMS-Wave simulations to obtain reliable estimates.

3.4.3 Test C3-Ex3: Mouth of the Columbia River, WA/OR

Description: The purpose of this test case was to validate CMS-Wave with data from the Mouth of the Columbia River (MCR) entrance located at the WA/OR border. The MCR entrance area poses severe challenges to navigation because of its harsh climate (i.e., influence of winds, waves, and tides). Severe storms and strong winds can occur unexpectedly, large waves impact the entrance in the fall and winter months, and the tidal range is high (2.1 m). These conditions cause significant sedimentation in the channel and erosion along beaches, and major damage to north and south jetties protecting the shipping channel. The MCR entrance is one of the most dynamic sites in the northwest region of the USA.

Directional wave data were collected by the U.S. Army Engineer District, Portland (Moritz 2005) between the north and south jetties from 1 August to 9 September 2005, at five monitoring stations. The incident wave spectrum was based on data from an offshore Buoy 46029 maintained by the NDBC since 1984 (http://www.ndbc.noaa.gov). Sample time-series of wind and wave data collected from Buoy 46029, and measurements in the entrance channel close to the south jetty, were compared. The effects of waves interacting with tidal current are clearly seen in the data as indicated by strong daily fluctuations of wave height, period, and direction.

Findings: Comparison of metocean data (winds, water levels, waves, and currents) between offshore buoys nearshore gauges at MCR indicated that waves experience significant changes in their transformation from deep to shallow water. CMS-Wave model predictions were validated with data obtained from field experiments using the statistics between the measured and calculated wave heights, periods, and directions. Calculations had a high correlation with data for measurements near the navigation channel in relatively deep water. As noted in the previous test case, for CMS-Wave applications to jettied inlets involving incident longer period waves (including the infragravity waves), nonlinear wave-wave interactions, and wave transmission and overtopping of breakwaters in numerical modeling is recommended. These mechanisms are required in such applications to obtain realistic results.

3.4.4 Test C3-Ex4: Southeast Oahu Coast, HI

Description: The purpose of this test case was to check the capability of CMS-Wave for wave predictions in the nearshore for the east central coast of Oahu that has fringing reefs. Directional wave data were collected at the southeast coast of Oahu, HI, for the Southeast Oahu Regional Sediment Management demonstration project conducted by the U.S. Army Engineer District, Honolulu. Data included three Acoustic Doppler Velocimeters (ADVs), installed nearshore from 9 August to 14 September 2005, offshore wave data from a CDIP Buoy 098, the ocean surface wind from NDBC Buoy 51001, and water level data from NOAA station 1612340 at Honolulu Harbor and Station 1612480 at Kaneohe Bay.

Findings: For this wave height calculation over a reef, CMS-Wave results agreed generally with the field measurements. In similar applications, a successful model performance may require a proper calibration of the model with the site specific data to determine an applicable bottom friction coefficient. The characteristics of waves (height, period, direction, wave-induced circulation) and wave nonlinearities reported by Demirbilek et al. (2007b) passing over reefs and surface roughness, surface irregularities, and reef face slope can affect the model's results significantly. A careful sensitivity analysis should be conducted to assess the effects of these processes and the associated parameters on model predictions.

3.4.5 Test C3-Ex5: Field Research Facility, NC

Description: The USACE Field Research Facility (FRF) at Duck, NC, has collected long-term wave data along a cross-shore wave array and two Waverider buoys. The array has four bottom mounted Nortek Acoustic Wave and Current (AWAC) sensors at depths of 5, 6, 8 and 11 m and two directional Waverider buoys at 17-m and 26-m depths. The Waverider buoy at 26-m depth was maintained by CDIP (Buoy 430), and data are available online at http://cdip.ucsd.edu. The wind measurements are available from NOAA coastal Station 8651370 at the end of the FRF Pier, and from a National Data Buoy Center (NDBC) directional wave Buoy 44014 at 48-m depth. The array and buoys spanned 95 km cross-shelf to capture the wave transformation processes from the outer continental shelf to within the surf zone (Hanson *et al.* 2009).

Findings: CMS-Wave simulations were not sensitive to different available breaking formulas used in the nearshore wave transformation at

the FRF during storms. CMS-Wave predictions with higher bottom friction resulted in a 25 percent or greater difference of wave height estimates and larger RMSE and MAE values (most readily observed during Hurricane Bill, an event with large swell). The best model performance was obtained by neglecting bottom friction while applying the Battjes and Janssen (1978) breaking formula with input wind measured at the FRF Pier and incident waves from CDIP 430.

CMS-Wave with the default values of parameters provided the best result as compared to data in storm wave simulations at the FRF. For a relatively small model domain, CMS-Wave was not sensitive to wind input in the simulation. Four different wave breaking formulations available in CMS-Wave all produced similar results. Overall, model-data agreement was better without including the bottom friction at the FRF simulations. It is important to note that CMS-Wave is a steady state model; when waves are changing during an evolving storm like a hurricane, larger errors can be introduced into the model's results.

3.4.6 Test C3-Ex6: Mississippi Coastal Improvement Program

Description: The Mississippi Coastal Improvements Program (MsCIP) has maintained two nearshore directional wave gauges (COE Gulf Gauge and Sound Gauge) at Ship Island, MS, as part of the barrier island restoration project (USACE 2010), that measured wave height and period. The wave direction was reported only if the wave height was greater than 0.1 m. The offshore wave data were available from a NDBC directional Buoy 42040 (165-m depth), located 90 km offshore Dauphin Island, AL.

Findings: The calculated wave height was better correlated to the measurements as compared to the wave period and direction. Overall, a better agreement was obtained for the Gulf Gauge than the Sound Gauge because the island sheltering degraded the Sound Gauge comparisons. The CMS-Wave results without bottom friction agreed better with measurements. For relatively low wave heights and short propagation distances on a sandy bed environment, model simulations indicated that the bottom friction was not an important factor.

3.4.7 Test C3-Ex7: Waves over a submerged rock reef, Indian River County, FL

Description: Directional wave information was collected by Surfbreak Engineering Sciences, Inc. (SES 2011) in Indian River County, FL, to quantify nearshore wave transformation over submerged rock reefs. An ADCP was installed offshore of the reef at the 9-m depth and an ADV was deployed inshore of the reef at 2-m to 3-m depth to measure current and waves.

Findings: CMS-Wave can be applied the wave transformation over the shallow reef if a large Manning's bottom friction is used in the simulations. More data for model calibration are required to assess similar mechanisms expected to induce damping.

4 Summary of V&V Study for CMS-Flow: Hydrodynamics (Report 3)

4.1 Introduction

Similar to CMS-Wave, three categories of tests were used to assess performance of CMS-Flow:

1. Analytical/empirical solutions (Category 1)
2. Laboratory studies (Category 2), and
3. Field experiments (Category 3)

Test examples chosen included some known analytical solutions and idealized problems, laboratory studies with data, and field studies with data. Many test cases not included in this V&V report are being researched and these will be documented in future companion reports. Statistical measures used to define the goodness-of-fit are slightly different than in Report 2, and are described in Appendix A. The following test cases for each category are included in this report.

4.2 Analytical solutions (Category 1 test cases)

The analytical and idealized cases described in this chapter were selected for verification of CMS-Flow to confirm that the intended numerical algorithms have been correctly implemented. The Category 1 test cases completed are:

1. Wind setup in a flat basin
2. Wind-driven flow in a circular basin
3. Tidal propagation in a quarter annulus
4. Transcritical flow over a bump
5. Long-wave runup over a frictionless slope

4.2.1 Test C1-Ex1: Wind setup in a flat basin

Description: This verification test was designed to test the most basic model capabilities by solving the most reduced or simplified form of the governing equations in which only the water level gradient balances the wind surface drag. The specific features of the model tested were (1)

spatially constant wind fields, (2) water surface gradient implementation, and (3) treatment of the land-water interface boundary condition.

Findings: The steady wind setup in a closed basin with a flat bed and irregular geometry was simulated, and the model performance was measured using several goodness-of-fit statistics. The model calculated the water level accurately from wind setup with RMSE of 0.01 percent, a MAE of 0.02 percent, and R^2 of 0.999. The test case demonstrated the model capability in simulating wind induced setup, and verified the implementation of both the wind driving force and water surface elevation terms.

4.2.2 Test C1-Ex2: Wind-driven flow in a circular basin

Description: The purpose of this test was to verify the steady state linear hydrodynamics when forced by spatially variable winds, a linear bottom friction, and with-and-without Coriolis force. Specific model features evaluated in this problem were spatially variable winds and Coriolis force.

Findings: The analytical solution for the steady-state wind-induced linear hydrodynamics in a closed circular basin was simulated. Computed water levels were accurate within 0.03 percent RMSE, and showed little influence from the staircase representation of the curved outer boundary. Current velocities were less accurate with a RMSE of 2.53 percent due to errors near the outer boundary where the grid did not resolve the curved feature perfectly.

For most coastal applications, open boundaries are represented by straight boundaries so the staircase boundary does not exist. Curved boundaries usually occur along the wet-dry interface in shallow water where current velocities are usually small due to the increased bottom friction. However, if the curved boundary occurs in deep water or in areas where the current velocities are strong, then errors will be incurred due to the staircase representation of the boundary. Nevertheless, the errors may be reduced by increasing the grid refinement along the specific boundary. In the future, this problem can be eliminated by implementing a boundary fitting method, such as a cut-cell or embedded boundary, or quadrilateral mesh.

4.2.3 Test C1-Ex3: Tidal propagation in a quarter annulus

Description: The purpose of this verification test was to assess the model performance in simulating long wave propagation. The case is useful for testing the model performance and symmetry for a non-rectangular domain with a tidal forcing specified on one of the curved boundaries. Because there is no bottom friction or mixing, the test case is also useful for looking at numerical dissipation.

Findings: The CMS-Flow can accurately simulate linear long-wave propagation in a quarter annulus with a linear bed, zero bottom friction and no Coriolis forcing. The water level RMSE, MAE, and R^2 were 3.3 percent, 2.7 percent, and 0.999, respectively. For practical applications, water level boundary conditions should be specified on straight boundaries. If a curved forcing boundary is necessary, then both water levels and current velocities should be specified.

4.2.4 Test C1-Ex4: Transcritical flow over a bump

Description: This test case assessed the simulation of flow in a mixed subcritical and supercritical regime. Due to a steep change in the bed elevation, the flow first changes from subcritical to a supercritical flow, and then back to subcritical flow. Because the bottom friction was not considered, an analytical solution was available for checking the calculated water level calculations.

Findings: Comparison of CMS-Flow to the analytical solution of flow over a bump verified that the calculated results were accurate for transcritical flows with sharp discontinuities. Both the implicit and explicit flow solvers produced similar results. The adaptive time step of the implicit solver increased the model efficiency and reduced the computational time. However, the implicit solution scheme is not recommended for practical applications in which the physics require small time steps due to sharp discontinuities in the flow and/or extensive wetting and drying. The small time steps required to resolve these rapidly-changing conditions means that the implicit solver would not be significantly more efficient than an explicit solver.

4.2.5 Test C1-Ex5: Long-wave runup over a frictionless slope

Description: The performance of the CMS-Flow in calculation of nonlinear long-wave runup over a frictionless planar slope was assessed by comparing the computed water levels and shoreline position with an analytical solution presented by Carrier et al. (2003).

Findings: Comparison of computed and analytical water levels and shoreline positions indicated good model performance as demonstrated by the goodness-of-fit statistics. The wetting and drying algorithm was found to be robust and led to an accurate prediction of the shoreline position.

4.3 Laboratory studies with data (Category 2 test cases)

These test cases include laboratory studies containing data, and were selected for validation of the CMS-Flow. These are generally process-specific validations to ensure that model can represent various coastal flow modeling processes correctly. The Category 2 test cases completed include:

1. Rectangular flume with a spur dike
2. Rectangular flume with a sudden expansion
3. Planar sloping beach with oblique incident regular waves
4. Idealized jettied inlet with equilibrium beach profile and oblique incident regular waves

4.3.1 Test C2-Ex1: Rectangular flume with a spur dike

Description: The CMS was applied to an experimental case of steady flow in a rectangular flume with a spur dike. The CMS performance was assessed by comparing the measured and calculated current velocities behind the spur dike. The specific model features tested were the nonuniform Cartesian grid, inflow flux boundary condition, outflow water level boundary condition, wall boundary condition and subgrid eddy viscosity (turbulence) model (Smagorinsky 1963).

Findings: In general, the computed current velocities agreed well with measurements using the default subgrid turbulence model with values of RMSE of 0.05 to 0.69 percent, MAE of 2.39 to 10.38 percent, and R^2 of 0.962 to 0.993. Further tests using different turbulence models and grid resolutions are needed to assess the model sensitivity. The nonuniform

Cartesian grid allows local refinement and is simpler to setup compared to the telescoping grid, but may require more computational cells.

4.3.2 Test C2-Ex2: Steady flow in a rectangular flume with a sudden expansion

Description: The CMS was applied to an experimental case of steady flow in a flume with a sudden expansion in width. The CMS performance was assessed by comparing the measured and calculated current velocities behind the sudden expansion. The specific model features tested were the stretched telescoping grid capability, inflow flux boundary condition, outflow water level boundary condition, wall boundary condition, and mixing-length eddy viscosity (turbulence) model (Wu et al. 2011).

Findings: The CMS-Flow performance was analyzed for a laboratory experiment of steady flow in a rectangular flume with a sudden expansion. The computed current velocities agreed well with measurements using the mixing-length turbulence model as demonstrated by the RMSE of 1.6 to 13.98 percent and R^2 ranging from 0.789 to 0.995. Further tests using different turbulence models and grid resolutions are needed to assess the model sensitivity. The stretched telescoping grid capability reduces the number of computational cells needed significantly. It is recommended that the stretched telescoping grid be used for practical applications whenever possible.

4.3.3 Test C2-Ex3: Planar sloping beach with oblique incident regular waves

Description: The CMS was applied to a laboratory experiment of wave-induced currents and water levels due to regular waves. The laboratory experiment with a large cross-shore gradient of wave height in the surf zone produced a large forcing useful for testing hydrodynamic model stability and performance. The specific CMS-Flow features tested were the surface roller, cross-shore boundary conditions, and combined wave-current bottom shear stress parameterization.

Findings: Wave-induced currents and water levels were simulated with the CMS for the case of monochromatic waves over a planar bathymetry. Results were calculated with and without the surface roller and the best results were obtained with the roller turned on, using a roller dissipation coefficient of 0.1 and a roller efficiency factor of 0.8. Both currents and

water levels were predicted with errors less than 10 percent. Additional tests will be conducted in the future to show model sensitivity to the calibration parameters and to better determine these parameters based on field conditions. The wave calibration and results are related to regular waves and are not directly applicable to field conditions. However, the purpose of these tests was to test the performance of the hydrodynamic model as quantified by the comparison between measured and simulated longshore current velocities and water levels under strong wave forcing.

4.3.4 Test C2-Ex4: Idealized jettied inlet with equilibrium beach profile and oblique incident regular waves

Description: The purpose of this validation case was to evaluate the CMS for wave-induced hydrodynamics in the vicinity of an inlet with two absorbing jetties. The specific model features to be tested were the inline flow and wave coupling, wave-adjusted lateral boundary conditions, and Stokes velocities in the continuity and momentum equations.

Findings: Laboratory experiments were used to validate the CMS for cross-shore and longshore currents and waves near an idealized inlet with two fully-absorbing jetties. Measurements of regular waves and wave-induced currents were compared with CMS simulations at the prototype scale. The CMS was run using mostly default settings, except for the Manning's coefficient (n = 0.025 sec/m$^{1/3}$) and roller dissipation coefficient (β_D = 0.05). Both parameters were held constant for all three cases. The value of the roller dissipation coefficient applied is the recommended value for regular waves. Model performance and behavior varied case by case but in general the calculated wave heights and wave-induced current velocities agreed reasonably well with measurements as indicated by the goodness-of-fit statistics. Calculated nearshore wave heights and currents upstream of a jetty were found to be within approximately 10 to 15 percent and 10 to 30 percent, respectively, of measurements. CMS-Wave was able to predict the location of the wave breaker accurately. However, tests were conducted in a physical model without tidal currents, winds, and with well known bathymetry and wave conditions, all of which represent additional potential sources of error in field applications.

These results indicate that, once the model is calibrated for a specific site using mainly the bottom roughness, the model may be applied at the same site for different wave conditions without having to recalibrate the model.

Using the wave- and depth-averaged hydrodynamic equations for depth-uniform currents as derived by Svendson (2006) improved the nearshore currents significantly and most noticeably by producing an offshore directed flow or undertow. Including the surface roller improved the longshore currents by moving the peak longshore current closer to the shoreline.

4.4 Field applications with data (Category 3 test cases)

The Category 3 V&V test cases completed are listed below. Additional cases are under investigation and will be included in future reports. Category 3 test cases completed are:

1. Gironde Estuary, France
2. Grays Harbor, WA
3. Ocean Beach, CA
4. St. Augustine Inlet, FL
5. Shark River Inlet, NJ
6. Galveston Bay, TX
7. Ship Island, MS
8. Hazaki Oceanographic Research Facility, Japan
9. Duck, NC
10. Matagorda Ship Channel, TX
11. Matagorda Ship Channel, TX (Salinity Transport)

4.4.1 Test C3-Ex1: Gironde Estuary, France

Description: Application of CMS to the Gironde Estuary demonstrated specification of the flow boundary condition within an estuary, with validation measurements of water level and current speed spaced along the axis of the estuary.

Findings: CMS calculations of tidal flow in a large estuary were compared to measured water level and current speed. Calculations agreed with measurements with errors ranging from 5 to 7 percent for water level and 7 to 21 percent for currents. The boundary condition used in the model was not measured exactly at the location of the boundary, and therefore the calculations incurred some error in phase lag of water surface elevation and in current velocities. This application demonstrates the accuracy of CMS within a macrotidal estuarine environment, for measurements distributed along the channel. Estimating the bottom

roughness based on the bottom type (sandy, rocky outcrops, vegetation, etc.), and then adjusting (calibrating) based on field measurements of water levels and currents, is recommended. When developing a new model setup and grid for engineering applications, it is useful to start simple as far as grid size and model forcing, and slowly increase the model complexity as needed until satisfactory results are obtained for the purpose of the project. This iterative process has the added benefit of providing insights on the importance of physical processes and model sensitivity to setup parameters and grid geometry.

4.4.2 Test C3-Ex2: Grays Harbor, WA

Description: The CMS performance in simulating the hydrodynamics and wave transformation at a relatively large and complex inlet and estuary at Grays Harbor, WA, was analyzed using field measurements of water levels and current velocities. The specific model features to be tested were the wave-flow coupling, user-defined water level boundary condition, and wetting and drying.

Findings: Water levels and depth-averaged principle current velocities were compared at several stations and four goodness-of-fit statistics were used to assess the model performance. In general, the model results agreed well with measurements. Although the model ramp period was only 24 hr, the time period for the model hydrodynamics to reach dynamic equilibrium in the bay (i.e. to fully spin-up) was approximately 250 hr. The model results demonstrated that it is reasonable to use large time steps on the order of 15 min for similar tidal inlet hydrodynamic studies. Using such a large time step will, however, reduce the accuracy of the wetting and drying. If this is considered to be an important aspect of the study, then a smaller time step should be used.

4.4.3 Test C3-Ex3: Ocean Beach, CA

Description: A hydrodynamics, wave, and sediment transport modeling study was conducted to evaluate a designated dredged-material placement site in the nearshore along a beach erosional hot spot, and to evaluate onshore nourishment alternatives at Ocean Beach, CA. A wide range of field data, including shoreline change, water levels, waves, current, and topographic mapping, have been collected by the San Francisco District (SPN) and the United States Geological Survey (USGS) at Ocean Beach and in San Francisco Bight from 2004 through 2010. For this application,

the offshore bathymetry data were obtained from GEOphysical DAta System (GEODAS) database, which has been developed and managed by the National Geophysical Data Center (NGDC) of NOAA.

Findings: Coupled CMS-Wave and CMS-Flow models gave excellent correlation using the default horizontal eddy viscosity scheme and bottom friction parameters. Goodness-of-fit statistics gave a relatively small RMSE of 8.4 to 11.7 percent between the model output and the ADCP velocity measurements within this high wave energy and strong tidal current region.

4.4.4 Test C3-Ex4: St. Augustine Inlet, FL

Description: The CMS performance in simulating tidal inlet hydrodynamics was tested using measured water levels and currents at St. Augustine Inlet, FL, in a study of mid-term evolution of the ebb tidal shoal in response to mining (U.S. Army Engineer District, Jacksonville 2010). This section presents validation of CMS to hydrodynamic measurements; validation of morphology change at St. Augustine Inlet is documented in the next chapter, and in Sánchez et al. (2011b).

Findings: The CMS was applied to a coastal inlet with tidal forcing. Calculated water levels agreed with two measurement locations with a correlation coefficient R^2 equal to 0.82-0.93 for the two measurement gauges. Measurements were made within the inlet throat, across the ebb shoal, and in the bay totaling 12 transects on 9 April 2010. These transects included three within the inlet throat and two across the ebb shoal during ebb flow, and three within the inlet throat and four within the bay on flood flow. Ebbing transects had normalized errors between calculated and measured values ranging from 1 to 11 percent for the inlet throat and 8 to 18 percent across the ebb shoal. For flooding transects, normalized errors ranged from 4 to 18 percent through inlet throat and up to 20 percent for bay transects during flood tide. This application demonstrated the ability of CMS to calculate water level and current within a tidally-dominated inlet system.

4.4.5 Test C3-Ex5: Shark River Inlet, NJ

Description: The CMS performance was tested with water levels and currents at Shark River Inlet, NJ. Water level data from Belmar, NJ, a site within Shark River Estuary, were compared to CMS calculations for a

10-day period from 15-25 August, 2009. Peak currents across three channel transects within the throat of Shark River Inlet measured during a complete tidal cycle on 20 August 2009 were also compared to CMS simulation results. The implicit time marching scheme of CMS-Flow was used and the model was forced with water level measurements at the Sandy Hook ocean tide gauge. Water level measurements at the Belmar tide gauge were used for model calibration. The case was useful for testing the CMS hydrodynamic performance for a relatively small bay and dual-jettied entrance. This section presents validation of CMS to hydrodynamic measurements; validation of channel infilling is documented in the next chapter, and in Sánchez et al. (2011b).

Findings: The CMS was applied to a coastal dual-jettied inlet with tidal current forcing provided to CMS-Flow from a gage 30 km north of the project site. Calculated water levels agreed with those measured in the project bay with a RMSE of 6 percent in magnitude and phase. Currents measured over a tidal cycle for three inlet cross-sections agreed with calculations with a MAE ranging from 3 to 9 percent. This application demonstrated the ability of CMS to calculate water level and current within a complex tidally-forced inlet system accurately.

4.4.6 Test C3-Ex6: Galveston Bay, TX

Description: The purpose of this validation case was to test CMS performance for tide and wind induced hydrodynamics in Galveston Bay. Measured data were compared to model results to calibrate and validate the model. Circulation in Galveston Bay is heavily dependent on wind forcing, providing an opportunity to test the capability of CMS to simulate these conditions.

Findings: Data collected during two time periods in 2010 were applied to validate the CMS for circulation. Measurements of water level and currents were compared with CMS results at multiple locations including the Galveston Entrance Channel, the channel between Galveston and Pelican Islands, mid bay, and the Gulf of Mexico offshore of the inlet. CMS was run using default settings. A spatially constant Manning's coefficient was calibrated to $n = 0.015$ sec/m$^{1/3}$ using measurements from one field study and applied to a separate field study as a validation case. Water levels were well represented at all measurement locations as quantified by the goodness-of-fit statistics. Measured currents compared well to modeled currents, except within the channel between Galveston and

Pelican Islands. Between the islands, magnitude of current speed is well captured; however, flow direction and phase are not. Increased resolution in the channel, accounting for the presence of large vessels, may improve results in this area.

Spatially constant wind forcing was sufficient for Galveston Bay for non-storm conditions. Although only Galveston Bay was tested, the same is probably true for other bays of similar or smaller size in Texas. Testing this assumption for each application and time period by comparing observed winds at multiple stations across the domain is recommended. Model results will be less accurate as the winds become less constant in space.

Poor grid resolution or bathymetry information over complex topography could result in locally less accurate results; however, lower grid resolution is often necessary away from the area of interest to increase computational speed.

When calibrating a model, starting by comparing water levels and then current velocities is recommended. This is because water levels are generally easier to calibrate and are less sensitive to errors in local bathymetry or poor grid resolution.

Manning's roughness coefficient was varied for calibration. In general, the value for this parameter should always be based on comparison of model results to measurements.

4.4.7 Test C3-Ex7: Ship Island, MS

Description: The purpose of this validation case is to test CMS performance for tide and wind induced hydrodynamics around Ship Island, MS, with-and-without regional model forcing.

Findings: The relatively small model domain allowed for the use of locally measured water levels and spatially uniform wind data for (non-storm) conditions. Similar results were obtained when the model was forced with spatially variable water levels from regional model results. Uniform winds proved sufficient in this application.

4.4.8 Test C3-Ex8: Hazaki Oceanographic Research Facility, Japan

Description: The CMS was applied to a field case to test calculations for the cross-shore distribution of the wave height and long-shore current over a double barred beach (Kuriyama and Ozaki 1993).

Findings: The implicit CMS was validated for wave height and longshore current distributions across a double barred surf zone. The case was run with-and-without the wave roller effect. For both simulations, wave height distribution across the surf zone was not influenced significantly by inclusion of the wave roller, and calculations had errors within 3 to 5 percent as compared to measurements. However, for the longshore current the calculations with the surface roller gave a better agreement. Both the peak location and the magnitude of the longshore current were better calculated with the roller effect. Since the roller model computation accounts for less than 1 percent of the total computational time, adding the roller calculation does not have a significant impact on the total computational time. Besides improving the accuracy of the longshore current, the roller has also added the benefit of improving model stability because it tends to spread out the combined wave and roller forcing. In the absence of longshore current measurements with which to calibrate and validate the model for site-specific studies, the surface roller should be included for practical applications in the surf zone.

4.4.9 Test C3-Ex9: Duck, NC, DELILAH field experiment

Description: The DELILAH data from a field experiment at Duck, NC, were applied to test the implicit CMS performance in predicting nearshore hydrodynamics, specifically the wave height and longshore current on a barred beach profile. The specific model features tested were the inline flow and wave coupling and surface roller.

Findings: Two cases were run with-and-without the wave roller effect. For both cases, wave height distribution across the surf zone was not significantly influenced by inclusion of the wave roller, and calculations were accurate within 3 to 5 percent of measurements for all cases with- and-without roller. The roller with a dissipation coefficient β_D = 0.02 gave the best correlation for longshore current speed which is lower than the typical range of 0.05 to 0.1 m/sec. More research is needed in determining the roller dissipation coefficient as a function of the field wave conditions. Similar to the previous test, both the location of the peak in the distribution

of the longshore current and the magnitude of the longshore current were better calculated with the roller effect. This case demonstrates the accuracy of CMS to calculate wave height transformation and longshore current speed in the surf zone.

4.4.10 Test C3-Ex10: Matagorda Ship Channel, TX

Description: The purpose of this validation case was to test CMS performance for tide and wind induced hydrodynamics in Matagorda Bay and Matagorda Ship Channel Entrance.

Findings: CMS-Flow was calibrated to water level data in the literature and then validated for water level data at two stations for typical summer and winter water levels, with correlation coefficients ranging from 89 to 96 percent. ADCP current measurements across the inlet throat were compared to CMS calculations at the same location. Results validated CMS for current speed with a correlation coefficient of 87 percent.

Similar to the Galveston test case, findings indicated that spatially constant wind forcing may be applied over bay-scale domains, even when it is a significant process. Although not specifically demonstrated for this case, testing this assumption for each time period by comparing observed winds at multiple stations across the domain is important. Model results will be less accurate as the winds become less constant in space. Incorporating a higher resolution grid that resolves spatial features such as coastal structures could result in longer run times. Depending on the area of interest and study objectives, lower resolution is often acceptable away from the area of interest to increase computational speed.

4.4.11 Test C3-Ex11: Matagorda Ship Channel, TX (salinity transport)

Description: The CMS was applied to Matagorda Bay, TX, to calculate depth-averaged salinity transport. Matagorda Ship Channel (MSC) is a federally-maintained inlet that, together with Pass Cavallo, connects the Matagorda Bay to the Gulf of Mexico and the Gulf Intracoastal Waterway (GIWW) (Kraus et al. 2006). The bay has an average water depth of 2 m and the hydrodynamics in this shallow bay are dominated frequently by wind. The mean tidal range is only 0.26 m, which very often results in a weak tidal forcing in the bay. Strong wind provides sufficient energy to mix water vertically, indicating that depth-averaged circulation and salinity

simulations are applicable to the bay as the salinity is well mixed over the water column.

An extensive field measurement program was conducted by Evans-Hamilton, Inc. (EHI) in 2005 (EHI 2006). The data collected include currents, water levels, salinity, total suspended solids, and waves throughout the bay. Freshwater inflows at the Colorado River and Lavaca River gages were available for this study from U. S. Geological Survey (USGS) website. The salinity measurements inside the bay were used to validate the CMS salinity calculations from 29 November to 10 December 2005.

Findings: Depth-averaged salinity calculations by the CMS were validated in Matagorda Bay with RMSE ranging from 13 to 27 percent. The model output showed close correlation with the observations and proper responses to wind and tide forcing. The coupled wave and current models demonstrated a successful application of salinity calculations in this shallow, well-mixed bay. The simulation of salinity can often require a 3-D solution due to the presence of vertical salinity gradients that can influence the flow significantly. It is therefore important to understand the limitations of 2-D salinity simulations, and to apply them only when the assumptions inherent in 2-D simulations are valid. However, when the application is well-mixed, a 2-D solution with CMS can represent salinity variation with forcing processes.

5 Summary of V&V Study for CMS-Flow: Sediment Transport and Morphology Change (Report 4)

5.1 Introduction

As described previously, verification is the process of determining the accuracy and numerical implementation of a model's governing equations. Calibration is the process of determining the unknown parameters or variables that represent physical quantities such as bottom roughness, or empirical coefficients and scaling factors for physical processes. Calibrating a model is achieved by tuning the model calculations to represent measured data. Almost all nearshore models for hydrodynamics, waves and sediment transport have calibration parameters and the development of appropriate values for different problems is still an active area of research. According to the authors' knowledge, there is no morphology change model that does not need to be calibrated for different problems. Many of the calibration parameters are due to simplification and parameterization of the physics. The process of determining the degree to which a model is an accurate representation of real world physics and processes from the perspective of the intended uses of the model is called validation. The objective of the sediment transport and morphology change V&V study was to verify the numerical implementations of advection and diffusion, and to validate the sediment transport model for various laboratory and field cases while showing the reader how the model should be calibrated for different problems. The same three categories were applied as in the previous Chapters: (1) Analytical or empirical solutions, (2) laboratory experiments, and (3) field studies.

5.2 Analytical/Empirical solutions (Category 1 test cases)

5.2.1 Description

This test case documented comparison of the CMS sediment transport calculations with analytical solutions available in the literature. The implemented numerical methods for advection and diffusion were verified with a one-dimensional analytical test case of the transport of a Gaussian shaped scalar quantity. Tests were conducted with and without the diffusion term using different grid resolutions and time steps to study the

model result sensitivity. Future tests will include 2-D advection and diffusion with source terms.

5.2.2 Test C1-Ex1: Scalar transport

Description: The CMS was applied to a one-dimensional (1-D) problem of scalar transport in an idealized rectangular domain to analyze the model performance in simulating the processes of advection and diffusion and assess numerical diffusion in the model as a function of time step and grid resolution.

Findings: Depth-averaged scalar transport calculations by the CMS were verified for the case of an idealized channel with constant water depth, current velocity and diffusion coefficient. The tests were conducted with and without the diffusion and sink terms. The best model results were obtained with the second-order Hybrid Linear/Parabolic Approximation (HLPA) scheme of Zhu (1991) advection. Computed results showed that simulations with large time steps and coarse mesh could generate extra numerical dissipation and result in excessive smoothing of the scalar field and thus underestimate of peak scalar values. To solve the transport problems with sharp gradients, a fine grid resolution and small time step were necessary.

Caution should be taken in selecting proper time step for a scalar transport simulation. Smaller time steps and finer grid resolutions can reduce numerical dissipation. It is possible to use a higher-order discretization for the temporal term to improve the results. However, the advantages of the higher-order approach are expected to be minor. There always is a compromise between numerical accuracy and computational cost. For most practical coastal sediment transport applications, the differences between first- and second-order advection schemes have been found to be insignificant, indicating that numerical dissipation is relatively small compared to physical diffusion. In addition, errors induced by transport capacity formulas, estimates of adaptation length, bathymetry, etc., are much greater and, therefore, it is hard to justify the use of high-order methods in morphodynamic models.

5.3 Laboratory studies with data (Category 2 test cases)

Cases presented in this chapter compare CMS calculations to six laboratory studies of sediment transport and morphology change. Three

cases consider channel infilling and migration: (a) in steady flows (Test C2-Ex1), (b) with waves parallel to the direction of flow (Test C2-Ex2), and (c) with waves perpendicular to flow (Test C2-Ex3). The other three cases are used to evaluate CMS capabilities for (d) combined wave-current transport in surf zone (Test C2-Ex4), (e) non-erodible hard bottom (Test C2-Ex5), and (f) non-uniform sediment deposition (Test C2-Ex6).

5.3.1 Test C2-Ex1: Channel infilling and migration: Steady flow only

Description: The CMS was applied to a laboratory flume study of channel infilling and migration due to a steady flow perpendicular to the channel axis. Model performance was evaluated by comparing measured and computed bed elevations of the channel cross-sections. Three channel cross-sections with slopes from 1:10 to 1:3 were simulated to test the limits of the depth-averaged model. Specific model features tested were:

1. Single-sized non-equilibrium total-load sediment transport,
2. Equilibrium inflow concentration boundary condition, and
3. Zero-gradient outflow boundary condition.

Findings: CMS was calibrated using one case and validated using the other two cases. A good agreement was obtained between computed and measured water depths as indicated by the goodness-of-fit statistics. The best results were obtained for the mild (1:10) channel slope test case. Measured bed elevations for the channels with side slopes of 1:7 and 1:3 indicated flow separation which is not accounted for in the present depth-averaged model.

5.3.2 Test C2-Ex2: Channel infilling and migration: Waves parallel to flow

Description: The CMS was applied to a laboratory case to study channel infilling and migration with collinear steady flow and regular waves. Specific model features tested were:

1. Inline wave-current-sediment coupling,
2. The single-sized non-equilibrium total-load sediment transport model, and
3. Sediment boundary conditions.

The model performance was tested using measured water depths and a sensitivity analysis was done for the transport formula, total-load adaptation length, and bed slope coefficient.

Findings: The CMS was applied to a laboratory experiment case of channel infilling and migration under steady flow and regular waves perpendicular to the channel axis (parallel to the flow). The non-equilibrium total-load sediment transport model was able to reproduce the overall morphologic behavior. A sensitivity analysis was conducted for three transport formulas, varying total-load adaptation lengths and bed slope coefficients. The results showed the importance of having an accurate sediment transport formula and how errors in the transport formula may lead to different calibration parameters. The bed slope coefficient was shown to be of secondary importance compared to the transport formula and adaptation length. For practical applications, running multiple simulations using different transport formulas and other model settings to assess sensitivity of modeling results is recommended.

5.3.3 Test C2-Ex3: Channel infilling and migration: Waves perpendicular to flow

Description: The CMS was applied to a laboratory case of channel infilling and migration with steady flow and random waves. The case is similar to the previous one except that the waves were parallel to the channel axis (perpendicular to flow). Specific model features tested in this case were:

1. Inline wave-current-sediment coupling,
2. Single-sized non-equilibrium total-load transport model, and
3. Sediment boundary conditions.

The model performance was evaluated using measured water depths and a sensitivity analysis was performed for the total-load adaptation length.

Findings: Coupled waves, currents, and non-equilibrium sediment transport were simulated with the inline CMS (single code) and computed water depths were compared to measurements. The goodness-of-fit statistics for the water depths indicated good model performance for total load adaptation lengths from 0.5 to 1.0 m. For practical applications, calibrating the adaptation length using measured morphology changes is recommended. Future research will be directed toward better under-

standing and predicting the adaptation length for a wide variety of conditions.

5.3.4 Test C2-Ex4: Large-scale Sediment Transport Facility

Description: Data from the Large-scale Sediment Transport Facility (LSTF) provide detailed measurements of wave height, water level, longshore current speed, and sediment transport (bed and suspended load) within a controlled laboratory environment. Application of the CMS to this test case demonstrated the model capability of calculating the cross-shore distribution of wave height, longshore current, and sediment transport from the wave breaker zone inshore.

Findings: The CMS was applied to LSTF Case 1 to compare with measured wave height, longshore current speed, water level, and sediment transport rate. Hydrodynamic comparisons were good, with errors of 3 to 4 percent and 9 to 12 percent for wave height and water level, respectively. Calculated longshore current speed agreed with measurements near the breaker line and into the surf zone, but the calculated peak current speed was offshore from the measurements, resulting in errors ranging from 18 to 24 percent. Calculations of sediment transport were conducted using three different formulas available in CMS. All formulas had a negative bias, meaning that they all under-predicted the magnitude of the mean sediment transport. Errors ranged from 22 to 26 percent, 26 to 32 percent, and 30 to 34 percent for the Lund-CIRP, Soulsby-van Rijn, and van Rijn formulas, respectively. Sediment transport calculations using the Lund-CIRP and Soulsby-van Rijn formulas were in better agreement from the breaker zone to mid-way through the surf zone. All formulas under-predicted sediment transport near the shoreline due to the lack of swash zone processes, which are being implemented presently in CMS. When comparing the net longshore sediment transport from CMS to estimates from sediment budgets, taking into account that the CMS will tend to under predict the longshore sediment transport due to the missing swash zone processes is important. As the LSTF experiments show, the longshore sediment transport in the swash zone can be significant and even larger than that in the surf zone. These tests demonstrated that CMS can be applied to calculate nearshore hydrodynamics and sediment transport within the calculated error bounds.

5.3.5 Test C2-Ex5: Clear water jet erosion over a hard bottom

Description: The CMS was applied to a laboratory case of a clear water jet in a rectangular flume with a sandy bed layer over a hard bottom from Thuc (1991). The experiment tests the sediment transport model under strong erosion conditions in the presence of a hard bottom.

Findings: The water depth BSSs calculated at 1 and 4 hr were good and excellent model performance, respectively. The water depth MAEs were approximately 19 and 6 percent at 1 and 4 hr, respectively. The sediment inflow loading factor was used to apply a clear-water boundary condition. Two important model features were tested: hardbottom and avalanching; both of which performed satisfactorily.

5.3.6 Test C2-Ex6: Bed aggradation and sediments sorting

Description: The CMS was applied to three laboratory cases of channel deposition with multiple-sized sediments. The laboratory experiments tested model capability for nonuniform sediment transport under transcritical flow conditions. The specific model features to be tested were the multiple-sized sediment transport, bed change and bed material sorting algorithms.

Findings: The CMS nonuniform sediment transport model was calibrated and validated using three laboratory experiments of channel aggradation and bed sorting. One experiment was used for calibration and the other two for validation. A fractional inflow sediment transport rate feature was used to specify an overloading at the upstream boundary. The upstream increase in bed elevation, downstream migration of the depositional fan, and mildly concave bed profile were well simulated. Bed elevations and water levels were reproduced with a MAE of approximately 3 and 2 percent, respectively. Results for the d_{50} and d_{90} varied but in general the model reproduced the downstream fining. Further analysis is necessary to study the influence of the transport scaling factors, and hiding and exposure coefficient on the bed composition.

When using the advanced multiple-sized sediment transport option in CMS, calibration should begin with the transport scaling factors and continue with the total-load adaptation length, as in the case of single-size sediment transport. If measurements or grain size distributions are available, then the hiding and exposure coefficient should be calibrated

next. For this study a value of 0.2 provided the best results using the van Rijn (1984a, b; 2007a, b) transport formula with a hiding and exposure correction based on Wu et al. (2000).

5.4 Field applications with data (Category 3 test cases)

Cases presented in this chapter compare CMS calculations to three field studies of nonuniform sediment transport and morphology change: (a) channel infilling at Shark River Inlet, NJ (Test C3-Ex1), (b) ebb shoal morphodynamics at St. Augustine, FL (Test C3-Ex2), and (c) nearshore morphodynamics at Grays Harbor, WA (Test C3-Ex3). Specific model features tested were: (a) inline wave-current-sediment coupling, (b) multiple-sized sediment transport, and (c) non-erodible hard bottom.

5.4.1 Test C3-Ex1: Channel infilling at Shark River Inlet, NJ

Description: This application compared the morphology change calculated with the CMS over a 4-month period to measurements of channel profiles and total infilling volume at Shark River Inlet, NJ, a dual-jetty coastal inlet system. Because of adjacent beach nourishment that provided a surplus of sand in the littoral system, Shark River had an increasing dredging requirement on time intervals roughly equal to 4 month cycles by 2009. Full documentation of the study is provided by Beck and Kraus (2010). Validation with measured water levels in Shark River Estuary and currents along three inlet channels during a tidal cycle is documented in Chapter 4 of this report, and Sánchez et al. (2011b). This section focuses on model setup and validation to channel infilling, providing insights into CMS morphologic capability on time scales corresponding to dredging cycles.

Findings: The CMS was applied to a coastal dual-jettied inlet with wave and tidal forcing. Hindcast wave data were provided to CMS-Wave at an offshore station and tidal forcing was provided from a gage 30 km north of the project site. Calculations presented herein demonstrated the CMS performance and capability in simulating channel infilling under combined wave-tidal forcing. Total infilling volume during a 4-month simulation, the time period between dredging, agreed with the total measured volume with a MAE of 3.4 percent. The mode performance was also tested using the water depth at selected transects. Two transects along the axis of the channel and three transects across-channel agreed with calculated transects with MAE between 2 to 11 percent. Calculation of sediment grain size

distribution during the 4-month simulation agreed qualitatively with general knowledge. That is, the CMS calculated armoring of more energetic regions with coarser sediment and deposition of finer sediment in quiescent regions. This application demonstrates the ability of CMS to calculate channel infilling accurately on engineering time scales typical of dredging intervals. Total magnitude and distribution of the shoaled sediment within the coastal navigation channel under the combined influence of waves and currents agreed with measurements with errors less than 11 percent.

5.4.2 Test C3-Ex2: Ebb shoal morphology change at St. Augustine Inlet, FL

Description: The CMS was validated with measured ebb shoal morphology change over a 1.4-year period at St. Augustine Inlet, FL, in a study of ebb tidal shoal evolution in response to mining (U.S. Army Engineer District, Jacksonville (SAJ 2010)). Validation of CMS to measured water level and current speed data is discussed in Chapter 4 of this report, and Sánchez et al. (2011a). This application demonstrated the capability of CMS to calculate evolution of inlet ebb shoal morphology as forced by combined waves and currents.

Findings: Calculated morphology change within the primary area of interest in the ebb tidal shoal had a total volume error ranging from 1 to 4 percent. This application demonstrates the ability of CMS to calculate morphology change volumes accurately over a 1.4-yr simulation within a wave-influenced, tidally-dominated inlet system.

5.4.3 Test C3-Ex3: Nonuniform sediment transport modeling at Grays Harbor, WA

Description: The CMS nonuniform sediment transport model was applied to the beaches adjacent to Grays Harbor, WA to test the model skill in predicting nearshore morphology change. The specific model features tested were bed material hiding, exposure, sorting, stratification, non-erodible bed surfaces, and transport due to asymmetrical waves, Stokes drift, roller and undertow. The model skill in predicting nearshore morphologic evolution was evaluated with the Brier Skill Score and other goodness-of-fit statistics.

Findings: Nearshore bathymetric measurements were used to validate the model during the period 6-30May 2001. Goodness-of-fit statistics of water depths and bed changes indicate generally reasonable to good model

performance, although the model skill varied significantly, especially on the beach face where swash zone processes were likely important and were not represented in the model. The measured bed change showed a larger degree of variability as compared to model results, indicating that nearshore morphology is sensitive to longshore variations in forcing and cross-shore processes which are difficult to resolve. Results also show that there is a region adjacent to the north jetty (transition zone) which is influenced strongly by the presence of the inlet due to wave refraction over the ebb-tidal delta, ebb and flood currents including detached eddies, and the north jetty.

6 Summary and Recommendations

This chapter summarizes the main findings of the CMS V&V studies and recommendations. The processes for which CMS has been verified and validated and are summarized, and values for parameters and settings for options available in CMS are recommended.

6.1 Summary

The CMS has been verified and validated successfully for the following processes, with a simple summary and their limitations as stated below:

6.1.1 Wave model

- Wind input, wave generation and growth: CMS-Wave was evaluated using analytical calculations in the literature, and proved to be reliable for wave generation and growth for coastal applications for different wind speeds. Additional testing is needed for CMS-Wave with field measurements. Wind-wave generation and growth over short fetches indicated that model results converged rapidly to the analytical solution for fetch lengths greater than 5 km.
- Wave-wave interactions: This capability of CMS-Wave needs additional testing. It has been compared to only one analytical solution, and although it appears to be robust, its validity for field applications over longer fetches and wind speeds should be confirmed with data. In shallow water and for very short fetch distances, the adapted formulation needs to be validated against a phase-resolving (Boussinsesq) model to determine if the resulting redistribution of wave energy in the wave spectra and change in the wave spectrum shape are modeled accurately. Once it is validated, this unique feature of CMS-Wave may improve model predictions in the large scale coastal regional sediment modeling applications.
- Wave diffraction at a breakwater gap: The general trends of wave diffraction calculations at a breakwater gap were well reproduced in comparison to approximated monographs available in the literature for engineering applications. Phase-resolving wave models should be used in projects where diffraction is strong and is the dominant wave process.
- Half- and full-plane versions of CMS-Wave: The half-plane version is recommended in practical application because it is computationally

twice more efficient. The full-plane version should be used in projects when incident waves exceed the 180-deg sector (half-plane) at the open boundary. The full- and half-plane capabilities of the model were validated with data from Matagorda Bay, TX, which is a large shallow bay (~ 2 m depth), and for measurements along the Mississippi Coast. For the Matagorda application, the bi-modal wave system that existed in the measurements could not be represented by calculation of single wave height and period parameters. The full-plane option was necessary to simulate combine local wave generation in the bay and waves entering the bay from the Gulf of Mexico. The full-plane model is slower generally and requires more computational resources.

- Wave diffraction and wave-structure interaction: Calculated wave height and direction were similar to an analytical solution of wave propagation through a breakwater gap for a distance of one wave length past the gap. As waves propagated further, the difference between model calculations and the analytical solution increased gradually. CMS-Wave may be used for relative comparisons between alternative designs during feasibility-level studies. For final design estimates, either a phase-resolving Boussinesq wave model or laboratory study is recommended.
- Wave breaking formulas: The Battjes and Janssen (1978) wave breaking formula was the most robust and is recommended for wave-current interactions at coastal inlets. The Extended Goda formula is the recommended alternative. CMS-Wave was validated for wave breaking on an ebb tidal current in an idealized inlet physical model. The Battjes and Janssen (1978) wave breaking formula produced the overall best results, so it is recommended as the default for all cases and not just currents. For the test cases investigated, wave-induced longshore currents on a planar beach showed a weak effect on wave breaking in the surf zone.
- Runup: Wave runup calculations were accurate for coastal structures and beaches with the seaward slope 1:5 or milder. For final design and complex situations with multiple or steeper slopes, a phase-resolving Boussinesq wave model or laboratory study should be used. Wave runup calculations for several sloping structures and different wave conditions agreed with laboratory measurements.
- Wave reflection, transmission, overtopping, wave-current interaction, long-period infragravity waves: Model results were shown to be appropriate for planning and feasibility-level studies. The model was validated for combined wave-current-structure interactions at

Cleveland Harbor. The model results were sensitive to the strong discharge (river flow) from the Cuyahoga River.

- Bottom friction: For sandy field sites, CMS-Wave provided best results without bottom friction. For sites with reefs and hard bottom, bottom friction should be specified based on available data.
- Combined wave shoaling, reflection, refraction, and diffraction: These processes were validated with data for a navigation improvement project at Grays Harbor and Half Moon Bay, WA. Water level variation had the most effect on calculated waves and currents in the nearshore. Model comparisons in inner Half Moon Bay, where diffraction is critical, showed comparatively higher error in wave height, period and direction.
- Wave-current interactions: CMS-Wave was validated for the high-energy environment including a navigation channel and jetties at the Mouth of the Columbia River, OR/WA. Wave sheltering and diffraction effects are strong at the North Jetty which protects from large waves from the northwest. Model results were less accurate in the sheltered diffraction zone than in the more exposed parts of the inlet.
- Wave propagation over reefs: This model feature was validated for two field sites, a rough reef protecting Southeast Oahu coast, HI, and a rocky coast at Indian River County, FL. For the Oahu case, large bottom friction coefficients were essential for accurate wave prediction. Calibration of the model with field data was required to get accurate results. For Indian River County, FL, calculations were sensitive to bottom friction coefficients and required calibration.
- Wave modeling for storms and hurricanes: CMS-Wave simulations of Atlantic storms and Hurricane Bill showed wave height variation in the cross-shore array at the FRF, NC. Wave heights tended to be over predicted for the northeasters and underpredicted for the Hurricane Bill swell.

6.1.2 Flow model

- CMS-Flow was verified with five analytical cases for wind-induced flow, tidal propagation, transcritical flow, and long-wave runup. Verification tests demonstrated the model accuracy in representing wind-induced currents, geostrophic balance, nonlinear long-wave transformation, wetting and drying, flux, water level, and land-water boundary conditions.
- Both the nonuniform Cartesian grid and telescoping mesh were verified with analytical test cases. The stretched telescoping grid with a

grid cell aspect ratio different than one is recommended since it can reduce the number of cells significantly.

- For boundaries which are not aligned with the Cartesian grid, errors associated with the staircase representation of the boundary may be reduced by increasing the local resolution either by subdividing the local cells as in the case of the telescoping mesh or by locally refining the resolution as in the case of nonuniform Cartesian grids. For practical applications, open boundaries should be specified along straight boundaries since the stair-case representation of curved open boundaries may lead to errors. For most practical applications, straight open boundaries are simpler to implement and curved open boundaries are not necessary.
- When applying the implicit flow solver to applications with sharp discontinuities in flow or extensive wetting and drying, smaller time steps are recommended to resolve physics associated with the rapidly changing conditions. The model will reduce the time step automatically to insure stability but this will consequently reduce the model efficiency. For problems which require small time steps due to large wetting and drying or rapidly varying conditions, using the explicit flow solver is recommended.
- CMS-Flow was validated with four laboratory experiments: a rectangular flume with spur dike extending into a steady flow, a steady flow with sudden expansion in the flume width, and two cases of wave-induced currents and water levels.
- The inline flow and wave coupling (steering) was tested using laboratory cases in which both the flow and wave models shared the same grid. Using the same grid for flow and waves avoids interpolation and extrapolation errors and is recommended whenever possible.
- The flux, water level, cross-shore, and land-water boundary conditions were tested for laboratory conditions and performed well without spurious flows or instabilities.
- Both the mixing-length and subgrid turbulence model performed well for laboratory test cases.
- For laboratory cases with regular monochromatic waves, the best results were obtained with the wave surface roller turned on. However, the optimal roller dissipation coefficient and efficiency factor varied for different tests.
- CMS was applied to 10 field data sets, including inlet systems connected to large estuaries, one with primarily river and tidal forcing, and the rest with wind, wave, and tidal forcing; beaches adjacent to a

large coastal inlet with strong tidal and wave forcing; and two nearshore experiments with high-quality surf zone measurements.

- For comparisons with two different field data sites, inclusion of the roller did not change the wave height distribution across the surf zone significantly, but the wave roller did improve the magnitude and location of the peak in the longshore current. In the absence of longshore current measurements, the roller should be included in nearshore simulations for best representation of the longshore current.
- Depending on the geometry of the application, either the nonuniform or telescoping Cartesian grid can be used. For most practical applications, the telescoping grid provides more flexibility and efficiency. Using a stretched telescoping grid is recommended whenever possible to reduce the number of cells.
- Default horizontal eddy viscosity and bottom friction parameters appeared to be appropriate for most cases. However, results can be sensitive to the bottom roughness. Therefore, calibration of the bottom roughness (e.g., Manning's coefficient) using field measurements estimated from coverage maps, or at least varied to obtain the model result sensitivity, is recommended.
- When calibrating a model using both water levels and current velocities, calibration should begin with the water levels because they are easier to calibrate generally and are less sensitive to errors in local bathymetry or poor grid resolution. The main calibration parameter usually is the bottom roughness (e.g., Manning's roughness coefficient). The bottom roughness should be estimated based on the bottom type (e.g., sand, mud, coral reef, rock, etc.), and then adjusted based on field measurements of water levels and current velocities. Test cases of wave-induced nearshore currents and water levels showed that the results can be sensitive to the surface roller breaking and efficiency coefficients. Lastly, the turbulent eddy viscosity is important for representing the nearshore hydrodynamics (e.g., longshore current profile, ebb/flood jet, rip currents, etc.) accurately. The default turbulence settings were found to work well for most practical applications. However, the optimal turbulence model and empirical parameters varied for different cases. Further research on the turbulence parameters is needed.
- It seems reasonable to apply spatially constant wind forcing over bay-scale domains for non-storm conditions, even when wind is a significant process. Testing this assumption for each time period by comparing observed winds at multiple stations across the domain is

important. When simulating storms, using both spatially variable winds and atmospheric pressure is recommended.
- For inlets connected to large tidal bays and estuaries such as Grays Harbor, WA, applying a spin-up period of 10 to 11 days or more is recommended for the system to reach dynamic equilibrium. The user can determine whether the system has reached dynamic equilibrium by comparing measured and computed water levels and current velocities and ensuring that the agreement between measurements and calculations does not continue to improve.

6.1.3 Sediment transport and morphology change model

- Two analytical cases were presented for 1-D scalar (e.g., sediment, salinity) transport: advection only, and advection-diffusion.
- The implicit time marching scheme was used to simulate the 1-D scalar advection, diffusion, and decay the computed results converged to the analytical solution for smaller time steps and grid resolution.
- For advection only, the first-order upwind was found to produce significantly more numerical diffusion than the second-order HLPA scheme. In addition to being more accurate, the HLPA scheme led to shorter run times due to faster solver convergence.
- For the combined advection and diffusion, results were found to be much less sensitive to the advection scheme and time step, indicating that the relative importance of numerical dissipation is relatively small compared to the physical diffusion. This partially explains why, for field applications, the differences between first- and second-order advection schemes are relatively small.
- Six laboratory data sets were compared with CMS calculations to investigate: channel infilling and migration; the cross-shore distribution of waves, currents, bed- and suspended-sediment transport; erosion of sand over hard bottom; and deposition of nonuniform sediments.
- Channel infilling calculations, one of the major applications of the CMS for the CIRP, was shown to give good agreement as compared to laboratory cases except for channels with steep side slopes (1:7 and 1:3), in which flow separation occurred. For cases with flow separation, a three-dimensional model may be required for more accurate estimates.
- The CMS calculated accurately surf zone processes for wave height, current speed (with surface roller activated), and sediment transport from the breaker zone to mid-way through the surf zone. Calculated longshore sediment transport rates may be underestimated near the

shoreline due to the lack of swash zone sediment transport, a feature that is presently under development in the CMS.
- Three field measurements of sediment transport and morphology change were compared to CMS calculations, including navigation channel, ebb shoal infilling, and multiple-sized sediment transport on a beach adjacent to a large tidal inlet.
- Infilling of navigation channels and an ebb shoal borrow area with wave, longshore current, and tidal current forcing was well reproduced by the CMS. In two field cases the calculated total infilling of the channel and borrow site agreed with measurements with errors of less than 11 percent. The CMS application was shown to be representative and useful for evaluating project alternatives such as channel realignment or deepening, ebb shoal mining, and jetty configurations.
- The CMS with nonuniform sediment transport calculated armoring of more energetic regions with coarser sediment and deposition of finer sediment in quiescent regions appropriately. This general sorting of nonuniform sediments in CMS was shown to be reasonable for mid-term (order of months to years) calculations. The natural self-stabilizing of the bed due to sediment sorting increased the model accuracy.

6.2 Recommendations

- It should be noted that the V&V study presented in this report was constrained by available measurement data. In several test cases, such as C2-Ex1, the CMS sediment transport model was first calibrated using one set of data and then validated using one or more separate sets of data. This calibration and validation was perfectly conducted. However, only a few cases have such detailed measurement data. In more general cases, such as case C2-Ex5 and C3-Ex1, only one experimental run was conducted but the data consisted of measurements at multiple times (time periods) or for multiple physical parameters; thus, the model was calibrated using part of the data (e.g., at one time or for one physical quantity) and then validated using the remaining data. In other cases, such as C3-Ex2 and C3-Ex3, the data were not sufficient to conduct both calibration and validation. Strictly, only calibration was conducted properly and validation was not warranted in these cases. However, these tests demonstrated that the model could reproduce reasonably the temporal and spatial variations of the physical quantities of the system using the calibrated parameters; thus, to certain extent, the model was also validated. Overall, the CMS sediment transport model has been verified and validated, and it has been calibrated in the selected

laboratory and field test cases. For future applications of this model, calibration is always preferred if measurement data are available. If no measurement data are available, a sensitivity study is recommended.

- The laboratory and field test cases demonstrated that the sediment transport capacity and adaptation length are two very important parameters in the Non-Equilibrium Transport (NET) model. Among these two parameters, the sediment transport capacity is more important than the adaptation length. When calibrating for sediment transport, start with the transport formula, then use the transport scaling factor, and finally the adaptation length. Other parameters such as the bed slope coefficient and bed porosity usually do not have a significant effect on the morphologic change. Measurements of bed- and suspended-load transport rates are rarely available for most coastal engineering projects, and the bed and suspended load transport scaling factors are calibrated typically by using estimates of longshore sediment transport or channel infilling rates. If no data are available for estimating transport scaling factors, it is then recommended that the default value of 1.0 should be used and a sensitivity study should be conducted using the typical range of 0.5-2.0. The CMS provides four formulas for sediment transport capacity under combined currents and waves. As shown in this report, different capacity formula will produce significantly different results and, therefore, the optimal transport formula for each application should be chosen based on measured morphologic response and sediment transport estimates.
- The total-load adaptation length between 0.5 and 1 m provided good model results for laboratory cases, whereas larger values between 10 and 100 m were used for field application cases. This implies that the adaptation length needs to be calibrated in applications if possible.
- To validate CMS fully, long-term seasonal to year-long field data from multiple gauge locations are needed at a structured inlet or entrance of a harbor protected by breakwaters and jetties. Short-term point measurements which provide piecemeal data from applications lack data quality control measures and instrumentation limitations. The latest field data collection technology has advanced significantly, and a comprehensive field measurement program at a navigation project is highly recommended. This field data collection study should include concurrent measurements of winds, waves, currents, water levels, frequent bathymetric surveys and bed change measurements, shoreline changes, structure foundation inspections, structural damage surveys, and shoreline response monitoring.

- A full-scale laboratory study is recommended for measurement of wave runup, overtopping, and transmission through and over jetty and rubble-mound breakwater structures. This proposed study should consider measuring detailed fields of waves and currents and also the bed changes as close to the structures as possible, with sufficient density for wave and flow measurements further from structures. The study should include upcoast and downcoast beaches, and measure waves and currents in the surf zone and swash zone along these beaches. The experiments should be repeated with hard and moveable beds of different types (sandy grain, mixed, and muddy bed). The data collected from this study would provide data necessary for process-specific validation of models and also validation of the overall model skills for combined processes.
- The V&V tests described in this report are insufficient to verify and validate comprehensively all of a numerical model's individual capabilities to determine confidently that a particular capability is ready for field applications. Much more research is needed and many more tests are necessary to determine limitations, strengths and capabilities of the CMS which have been partially investigated in this report. Consequently, the continuation of this V&V activity and additional testing of the model, with periodic reporting in a series of future companion reports, is recommended. This activity will provide USACE with a unique data set that can be used in the future with any coastal model, existing or new.
- The results of V&V studies should be published in peer-reviewed journal papers to increase the confidence in the scientific aspects of ERDC modeling capabilities and to attract commercial users' interest in these tested models. For consistency, ERDC should use these same datasets in the approval and certification of its numerical models. The CIRP V&V study reports and the associated data are posted to ERDC and/or CHL websites for worldwide user access by the peer community, and especially for special needs of District users.
- All laboratory cases studied were for steady conditions. In the future, validation using laboratory hydrodynamic tests for unsteady conditions should be conducted.
- Turbulence calculations performed well in the test cases discussed herein. However, optimal empirical coefficients for each turbulence model varied depending on the case. Although these tests provide a reference for similar applications, they are not sufficient to provide guidance for different applications. More tests are necessary for

developing comprehensive guidance for turbulence coefficients. Presently, all of the turbulence models in CMS assume local equilibrium between turbulence production and dissipation. This has the advantage of not having to solve additional transport equations for turbulence and possibly other turbulence variables (e.g. energy dissipation, frequency of dissipation, etc). However, more sophisticated turbulence models may prove beneficial for some coastal applications and require less calibration than simpler models. In the future, an improved turbulence model can be implemented that simulates the production, transport and dissipation of turbulence (e.g., Rastogi and Rodi 1978). This topic should be researched further in the near future.

- Inclusion of the surface roller improved the magnitude and location of the peak longshore current significantly. The surface roller has the added benefit of increasing model stability. However, in one case, the best value of the dissipation coefficient was 0.02, and was varied in the recommended range of 0.05 to 0.1. More case studies should be evaluated to investigate the best magnitude of this parameter as a function of field forcing, and guidance will be provided for estimating this parameter in the absence of longshore current data.
- In the SMS 11.0 interface, telescoping grids are limited to a spatially constant cell aspect ratio. The present numerical discretization of the telescoping grid allows for anisotropic grid refinement and spatially variable aspect ratios. However, these options should be implemented in the interface in the near future.
- The errors at curved boundaries of CMS grid domain can be minimized by applying local refinement to better resolve curvature of the boundaries. However, this increases the number of cells and still produces a staircase representation of curved boundaries. In the future, this problem could be eliminated by implementing a boundary fitting method, such as a cut-cell, shaved-cell techniques (e.g., Popinet and Rickard 2006) or immersed boundaries (e.g., Ye et al. 1999).
- For the implicit solver, the governing equations are discretized into a linear system of equations. The resulting matrix is solved using one of four general solvers for sparse unsymmetrical matrices. The model's computational efficiency can be improved by implementing special matrix solvers such as the Alternate Direct Implicit (ADI) and Strongly Implicit Procedure (SIP), which take advantage of the mesh structure and are more efficient. Regular Cartesian grids have the advantage that several efficient matrix solvers are available.

- Additional verification (analytical) tests are needed for two-dimensional problems with source terms.
- Additional tests should be performed to estimate the adaptation length appropriate for coastal applications as a function of forcing conditions and sediment characteristics.
- The implementation of the swash zone processes within the current 2-D framework to simulate shoreline change and represent longshore sediment transport rates are challenging and should be considered in future studies. Representation of cross-shore sediment transport processes, primarily wave asymmetry and undertow, to better simulate the onshore and offshore migration of sediments, need additional model developmental work and field testing.
- Additional studies are needed to quantify the mechanisms of nonuniform sediment transport, morphology change, and bed material hiding, exposure, and armoring.

All the data sets discussed in this report are described in much greater detail in the accompanying series of CMS V&V Reports 2, 3 and 4. These reports and associated files for all test cases will be applicable to verification and validation of other numerical models. These resources are available from the CIRP website[1].

[1] http://cirp.usace.army.mil/

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Appendix A: Goodness-of-fit Statistical Error Metrics

Several statistical measures are used in the CMS V&V study as "goodness-of -fit" error metrics to characterize the degree of agreement obtained between a model and data. Reports 2, 3, and 4 provided details of how various statistics have been used in waves, flow, and sediment transport test cases. The common metrics used included the Root-Mean-Square Error (RMSE), Correlation Coefficient (R) or Coefficient of Determination (R^2), Mean Absolute Error (MAE), and Bias. Aside from some minor variations in the mathematical definition of these metrics, for completeness their definitions are provided below.

Root Mean Square Error: $$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(x_{c,i} - x_{m,i}\right)^2}{N}} \tag{B-1}$$

The RMSE has the same units as the measured data, with lower values of RMSE indicating a better match between measured and computed values. The RMSE can also be applied as a normalized value by dividing the above value with the range of data (e.g., max value of data – min value of data).

Correlation Coefficient: $$\mathrm{R} = \frac{\sum_{i=1}^{N}\left(x_{c,i} - \overline{x_c}\right)\left(x_{m,i} - \overline{x_m}\right)}{\sqrt{\sum_{i=1}^{N}(x_{c,i} - \overline{x_c})^2}\sqrt{\sum_{i=1}^{N}(x_{m,i} - \overline{x_m})^2}} \tag{B-2}$$

The squared correlation coefficient R^2 is also used in some of the case studies herein, with the following qualifications for the degree of correlation: $0.7<R^2<1$ (strong), $0.4<R^2<0.7$ (medium), $0.2<R^2<0.4$ (small), and $R^2<0.2$ (none or weak).

Mean Absolute Error: $$\mathrm{MAE} = \frac{\sum_{i=1}^{N}\left|x_{c,i} - x_{m,i}\right|}{N} \tag{B-3}$$

The MAE can be expressed in units of percent, and like the RMSE, it can also be normalized by the range of data. Smaller values of MAE indicate a good agreement between measured and calculated values.

Bias: $$\mathrm{Bias} = \left\langle x_c - x_m \right\rangle \tag{B-4}$$

Positive values indicate overprediction and negative values indicate underprediction.

Brier Skill Score (BSS): $$\mathrm{BSS} = 1 - \frac{\left\langle (x_m - x_c)^2 \right\rangle}{\left\langle (x_m - x_0)^2 \right\rangle} \tag{B-5}$$

The BSS generally ranges between 0 and 1, with a value of 1 indicating a perfect agreement between measured and calculated values. Scores equal to (or less than 0) suggest that the mean observed value is as or more accurate than the calculated values. The following quantifications are used for describing the BSS values: 0.8<BSS<1.0 (excellent), 0.6<BSS<0.8 (good), 0.3<BSS<0.6 (reasonable), 0<BSS<0.3 (poor), and BSS<0 (poor or none).

In the above equations, *c* refers to calculated values, *m* to measured values, and *o* denotes the mean values. The terms $x_{c,i}$ and $x_{m,i}$ are the *i*-th calculated and measured values, respectively, in a total of i = 1 to N samples; $\overline{x_c}$ and $\overline{x_m}$ are the mean values of $x_{c,i}$ and $x_{m,i}$, respectively. The angled brackets indicate averaging. These definitions as used here refer to an individual test in an experiment or to a specific gauge data within a test. Furthermore, the values of "*x*" represent any calculated parameters by wave, flow and sediment transport models, such as the zero-moment wave height, peak or mean period, peak and/or mean direction, current speed, current direction, water surface elevation, or bed change, etc. Consequently, these are not "samples" in the sense of standard sample measured time series of the water surface in experiments or calculated spectral wave parameters, but post-processed results of those samples.

For information, it should be noted that the Pearson correlation coefficient (R) and coefficient of determination (R^2 = R*R), both dimensionless, are most frequently used in engineering works to indicate agreement between different datasets (e.g., numerical model results and data). The values of R

vary between -1 and 1, while R^2 is accordingly bounded between 0 and 1. Because R measures the linear co-variation between two datasets, higher R or R^2 indicates that the two datasets have similar linearly spatial or temporal patterns. However, the use of R or R^2 can be sometimes misleading to measure data agreement because they fail to measure the actual difference between two datasets. Consequently, neither R nor R^2 alone are a good measure of data agreement, and additional statistics are required to quantify the agreement between model and data. The mean bias is a simple algebraic difference between datasets $x_{c,i}$ and $x_{m,i}$ of sample size N, which measures the average difference between the two datasets.

The MAE, RMSE, and Bias metrics measure the actual differences between two different datasets, but they are not standardized and not bounded. When these error measures are expressed as percentage errors and normalized in some fashion, they become standardized and are independent of the unit of data. To remedy the shortcomings of these individual metrics, Willmott (1981, 1982) developed the so-called index of agreement that embodies R, R^2, MAE, and RMSE in a single expression. This metric is non-dimensional and bounded between 0 and 1. Each of the above and many other error measures which are used in engineering and science have certain advantages and disadvantages. Related publications in the References provide details of this topic. It suffices to note that the metrics used in this study are among the most commonly used ones in engineering works.

Appendix B: Annotated Bibliography of Coastal Modeling System Applications

Introduction

Appendix B presents a compilation of publications that have applied the Coastal Modeling System's (CMS) wave or flow models independently or for an integrated wave, flow, and sediment transport study. For some of these studies, the precursor to the CMS's flow model, CMS-M2D, was applied. Other studies coupled the CMS with external circulation, wave, and/or sediment transport models, as noted. The purpose of the annotated bibliography is to provide the reader references for more detailed investigation into types of CMS applications that have been conducted in the past.

In the following section, each application and the problem that was addressed are described, followed by the reference. Discussions are organized alphabetically by the reference. All references are available from the Coastal Inlets Research Program (CIRP) website under "Publications[1]."

A partial list of CMS applications

Mattituck Inlet, NY

Description: Wave, circulation (CMS-M2D), and sediment transport models were applied to evaluate nearshore processes with and without the Federal navigation project at Mattituck Inlet, NY.

Reference: Batten, B. K., and N.C. Kraus. 2006. Evaluation of Downdrift Shore Erosion, Mattituck Inlet, New York: Section 111 Study. *Technical Report ERDC/CHL-TR-06-1*, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/pubs/html/batten-kraus-06.html

Shark River Inlet, NJ

Description: Three reports detail phases of a CMS application to quantify the magnitude and location of channel infilling for various navigation channel alternatives. Options to reduce the frequency of

[1] http://cirp.usace.army.mil/pubs/ .

Operation & Maintenance dredging (~ every 3-4 months) were investigated.

References:

Beck, T.M. and N.C. Kraus. 2010. Shark River Inlet, New Jersey, Entrance Shoaling: Report 2, Analysis with Coastal Modeling System. *ERDC/CHL-TR-10-4*, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/pubs/html/10-Beck-Kraus_TR-10-4.html

Beck, T.M. and N.C. Kraus. 2011a. **Ebb-Tidal Delta Development Where Before There Was None, Shark River Inlet, New Jersey**. *Proceedings Coastal Sediments 2011*. http://cirp.usace.army.mil/Downloads/PDF/CS11_Beck-Kraus.pdf

Beck, T.M. and N.C. Kraus. 2011b. New Ebb-Tidal Delta at an Old Inlet, Shark River Inlet, New Jersey. *Journal of Coastal Research*, Coastal Education and Research Foundation, Inc., Special Issue, No. 59, pp 98-110. http://cirp.usace.army.mil/pubs/jarticles.html

Two dual-inlet systems in west-central Florida

Description: This study investigated the morphodynamics of four inlets (Johns Pass, Blind Pass; New Pass, Big Sarasota Pass, FL) in two multi-inlet systems. The CMS was applied to evaluate the influences of channel dredging on the flow patterns over the ebb tidal delta and sediment bypassing with wave, current, sediment transport, and morphology change calculations. The CMS reproduced the observed medium-term morphology changes, and applications explored the influence of channel dredging on inlet morphodynamics.

Reference:

Beck, T.M., and P. Wang. 2009. Influences of channel dredging on flow and sedimentation patterns at microtidal inlets, West-central Florida, USA. *Proceedings Coastal Dynamics 2009*. http://cirp.usace.army.mil/Downloads/PDF/CD09_Beck_Wang.pdf.

Ocean City Inlet, MD

Description: The CMS (the previous version of hydrodynamic modelCMS-M2D, and an earlier version of the wave model WABED) were run in a coupled mode to evaluate the forcing processes and pathways for inlet bypassing. The application evaluated the influence of mining sand from the outer lobe of the ebb tidal shoal on the updrift and downdrift beaches.

Reference:

Buttolph, A.M., W.G. Grosskopf, G.P. Bass and N.C. Kraus. 2006. Natural Sand Bypassing and Response of Ebb Shoal to Jetty Rehabilitation, Ocean City Inlet, Maryland, USA. *Proceedings 30th Coastal Engineering Conference*. World Scientific Press, pp. 3344-3356. http://cirp.usace.army.mil/Downloads/PDF/ICCE06_Buttolph_et_al_Ocean%20City.pdf.

Mobile Pass, AL

Description: Using a regional circulation model to provide boundary conditions, the CMS was applied in a coupled mode with a wave model to indicate sediment transport pathways and morphologic change on the ebb tidal delta. Results suggested that wave-driven transport dominated changes in bathymetry offshore Mobile Pass. Although morphology change predictions were considered qualitative in nature, trends revealed from the modeling work closely simulated findings based on analysis of the historical bathymetric change.

Reference:

Byrnes, M.R., S.F. Griffee and M.S. Osler. 2010. Channel Dredging and Geomorphic Response at and Adjacent to Mobile Pass, Alabama. *ERDC/CHL-TR-10-8*. US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/pubs/html/10-Byrnes_TR-10-8.html.

Grays Harbor, WA

Description: Wave and hydrodynamic modeling results from CMS-Wave, and a regional circulation model for the existing and realigned channels, were used in the sediment modeling for the associated short- and long-term sediment transport at Grays Harbor. Sediment transport modeling was performed using external cohesive transport and plume fate models.

Reference:

Demirbilek, Z., L. Lin, J. Smith, E. Hayter, E. Smith, J.Z. Gailani, G.J. Norwood and D.R. Michaelsen. 2010. Waves, Hydrodynamics and Sediment Transport Modeling at Grays Harbor, WA. *ERDC/CHL-TR-10-13*. US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/pubs/html/10-Zeki-Lin_TR-10-13.html.

Mouth of the Colorado River, TX

Description: The CMS was applied as part of a multidisciplinary approach to evaluate inlet processes in a preliminary design of new jetties to reduce the dredging requirements at this shallow-draft channel. A regional circulation model provided boundary conditions for CMS (wave, flow, and sediment transport) in an evaluation of six alternative designs.

Reference:

Kraus, N. C., L. Lin, E.R. Smith, D.J. Heilman and R.C. Thomas. 2008. Long-Term Structural Solution for the Mouth of Colorado River Navigation Channel, Texas. *ERDC/CHL-TR-08-4*. US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/Downloads/PDF/CHL-TR-08 -4.pdf

Kawaihae Harbor and Pelekane Bay, HI

Description: These two publications document CMS wave, current, and sediment transport applications to assess the benefits in terms of increased circulation, water quality, and long-term viability (rate and magnitude of channel shoaling) for a proposed channel connecting Kawaihae Harbor and Pelekane Bay.

References:

Li, H., M.E. Brown, N.C. Kraus, T.D. Smith and J.H. Podoski. 2010. **Evaluation of Proposed Channel on Circulation and Morphology Change at Kawaihae Harbor and Pelekane Bay, Hawaii, USA**. *Proceedings of the International Conference on Coastal Engineering*, No. 32(2010), Shanghai, China. Paper number: Sediment.79. http://journals.tdl.org/ICCE/ .

Li, H., M.E. Brown, T.D. Smith and J.H. Podoski. 2009. Evaluation of Proposed Channel on Circulation and Morphology Change at Kawaihae Harbor and Pelekane Bay, Island of Hawaii, HI. *ERDC/CHL-TR-09-19* US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/pubs/html/09-Li-Brown_TR-09-19.html

Dana Point Harbor, CA

Description: The CMS was applied to investigate wave, current, circulation patterns, and sediment transport in the vicinity of the Dana Point Harbor breakwater system. Options to calculate wave transmission and sediment transport through rubblemound structures were validated with measured waves, currents, and channel deposition inside the harbor.

Reference:

Li, H., L. Lin, C. Lu and A.T. Shak. 2011. **Evaluation of Breakwaters and Sedimentation at Dana Point Harbor, CA**. *Proceedings Coastal Sediments 2011*. http://cirp.usace.army.mil/Downloads/PDF/CS11_Li-Lin.pdf .

Willapa Bay, WA

Description: The CMS (wave and flow) was applied to a barrier island located inside Willapa Bay to evaluate the storm impacts with and without dune restoration. Sediment for the restoration would be mined from the Willapa Bay north entrance channel and placed to create dunes on the island. Results indicated that the risk of inundation from a selected historical storm was reduced from 54 percent to 7 percent with the restoration.

Reference:

Michalsen, D.R., S.D. Babcock and L. Lin. 2010. **Barrier Island Restoration for Storm Damage Reduction: Willapa Bay, Washington, USA.** *Proceedings of the International Conference on Coastal Engineering*, No. 32(2010), Shanghai, China. Paper number: Management.32. http://journals.tdl.org/ICCE/ .

Packery Channel, TX

Description: Low-frequency, low-amplitude waves were believed to have caused damage to a boat ramp inside Packery Channel, TX, resulting from Tropical Storm Erin (August 2006) and Hurricane Ike (September 2007). The CMS (wave and flow) results indicated that small amplitude long-period waves generated offshore during storms can propagate through the Packery Channel and yield sufficient energy in the vicinity of the boat ramp to cause severe damage. The wave impacts were accentuated by the geometry of the boat ramp.

Reference:

Reed, C.W. and L. Lin. 2011. Analysis of Packery Channel Public Access Boat Ramp Shoreline Failure. *Journal of Coastal Research Special Edition*, Coastal Education and Research Foundation, Inc., Special Issue, No. 59, pp 150-155. http://cirp.usace.army.mil/Downloads/PDF/JCR_NCK_Symposium-ReedLin.pdf.

Matagorda Ship Channel, TX

Description: The landcut for the Matagorda Ship Channel narrows from 2,000 ft to 950 ft (referred to as the bottleneck), greatly focusing the flow

and increasing the current velocity in this area, causing difficulties in navigation. The CMS (wave, flow, and sediment transport) was applied to evaluate bottleneck removal alternatives and placement of the sediment to increase the size of a beneficial use island in the bay. The interaction between the entrance and an adjacent natural inlet was also examined.

Reference:

Rosati, J., A.E. Frey, M.E. Brown and L. Lin. 2011. Analysis of Dredged Material Placement Alternatives for Bottleneck Removal, Matagorda Ship Channel, Texas. *ERDC/CHL-TR-11-2*. US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/pubs/html/11-Rosati-Frey-TR-11-2.html

Shinnecock Inlet, NY

Description: The CMS calculated channel infilling for laboratory and field applications. The field site was Shinnecock Inlet over a 9.5-month period, calculations were compared to measured volume change on the outer ebb shoal, deposition basin, and bypass bars, and confirmed generally-accepted ranges for longshore sand transport rates.

Reference:

Sanchez, A. and W. Wu. 2011. A Non-equilibrium Sediment Transport Model for Coastal Inlets and Navigation Channels. *Journal of Coastal Research Special Edition*, Coastal Education and Research Foundation, Inc., Special Issue, No. 59, pp 39-48. http://cirp.usace.army.mil/Downloads/PDF/JCR_NCK_Symposium-Sanchez.pdf

Sabine Pass, TX

Description: CMS-Wave and CMS-Flow were applied as a part of this study to evaluate wave, currents, and cohesive sediment transport shoaling (a proxy was applied to represent cohesive transport) for jetties and the navigation channel in its present-day and future (+50 years) conditions incorporating relative sea level rise, consolidation of the jetty system, and anticipated storms.

Reference:

Seabergh, W.C., E.R. Smith and J.D. Rosati. 2010. Sabine-Neches Waterway, Sabine Pass Jetty System: Past and Future Performance. *ERDC/CHL-TR-10-2*. US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/pubs/html/10-Seabergh_TR-10-2.html

Breach adjacent to South Jetty, Grays Harbor, WA

Description: The CMS-Flow (CMS-M2D) was applied in conjunction with a regional circulation model and a coupled wave model to evaluate the evolution of a future breach adjacent to the south jetty at Grays Harbor, and assess the impact to the Federal Navigation Project. The CMS calculated tidal and wave-induced currents through the breach to assess the potential for continued breach growth and long-term assessment of breach stability.

Reference:

Wamsley, T. V., M.A. Cialone, K.J. Connell and N.C. Kraus. 2006. Breach History and Susceptibility Study, South Jetty and Navigation Project, Grays Harbor, Washington. *ERDC/CHL-TR-06-22*. US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi. http://cirp.usace.army.mil/pubs/html/wamsley-cialone-connell-06.html.

Johns Pass and Blind Pass, FL

Description: CMS was applied to calculate wave, current, sediment transport, and morphology change over 1.2 and 1.6 years at a dual-inlet system in west-central Florida. Calculated hydrodynamics agreed with observations, including a dominance of tidal flow through Johns Pass as compared to Blind Pass, and wave refraction and breaking patterns over the ebb tidal deltas and along the adjacent shorelines. Sedimentation in the Blind Pass channel was calculated as 32,000 m^3/yr, agreeing with the measured value of 35,000 m^3/yr with a similar spatial distribution pattern. The computed sedimentation rate of 60,000 m^3/yr at a designed dredge pit on the Johns Pass ebb-delta agreed with the generally accepted gross longshore transport rates. Simulations reinforced the belief that rapid and large morphologic change occurs during high wave energy conditions.

Reference:

Wang, P. and T.M. Beck. 2011. Modeling Regional-Scale Sediment Transport and Medium-term Morphology Change at a Dual-Inlet System Examined with the Coastal Modeling System (CMS): A Case Study at Johns Pass and Blind Pass, West-central Florida. *Journal of Coastal Research*, Coastal Education and Research Foundation, Inc., Special Issue, No. 59, pp 49-60. http://cirp.usace.army.mil/Downloads/PDF/JCR_NCK_Symposium-Wang.pdf.

Sebastian Inlet, FL

Description: The CMS (circulation, wave, and sediment transport) was applied to calculate the morphology change and determine the influence of limestone rock outcrops (represented with the hard bottom feature) on inlet dynamics. Morphologic evolution was associated with the ebb-jet and wave-induced transport. General patterns of ebb shoal growth, sand bypassing, and scour of the channel banks and around the jetties were reproduced by the model.

Reference:

Zarillo, G. A. and F.G.A. Brehin. 2007. Hydrodynamic and Morphologic Modeling at Sebastian Inlet, FL. *Proceedings Coastal Sediments '07 Conference*, ASCE Press, Reston, VA, 1297-1310. http://cirp.usace.army.mil/Downloads/PDF/CS07_Sebastian_Inlet_FL_Hydro_Sed-Zarillo-Brehin.pdf.

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14. ABSTRACT

This report summarizes the framework and provides key findings of the Verification and Validation (V&V) study for the Coastal Modeling System (CMS), a product of the Coastal Inlets Research Program (CIRP). There are three components of the study: Verification, Calibration, and Validation, and these are termed for simplicity as "V&V" herein and in the companion reports. This is the first report, Report 1, in a series of four reports, and it provides a synopsis of the major findings from the other three reports. Verification & Validation was performed for three main components of the CMS: CMS-Wave (Report 2), CMS-Flow (Report 3) and Sediment Transport and Morphology Change (Report 4). This Summary is intended for engineers and scientists considering whether the CMS would be appropriate for their projects, (after which they may study the other V&V reports), and for managers and decision-makers so that they will have a succinct resource detailing the performance of each CMS component as well as the integrated modeling system.

The overall V&V study was separated into three functional areas to assess the predictive skills of the CMS critically; specifically, for modeling waves, circulation, and sediment transport and morphodynamics for a wide variety of coastal inlet, navigation channel, bay, estuary, and adjacent beach problems. To achieve this goal, each evaluation began by verification of the model of focus by comparing its predictions to analytical or empirical solutions for purposes of testing the basic physics and computational algorithms implemented in a given model. These fundamental evaluations were followed by a set of applications with data available either from laboratory or field investigations, which were used to validate the models. The validation cases represent real world problems, typical applications for which CMS is applied within the coastal navigation mission area. For the Flow, and Sediment Transport and Morphology Change applications, the CMS suite of models were calibrated prior to validation using data from a number of past and present District project applications with

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